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Indirect Bonding Method: *in vitro* Comparison of the Shear Bond Strength Between Metallic Orthodontic Brackets and Different Porcelain Surface Preparations

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Ce mémoire intitulé:

Indirect Bonding Method: *in vitro* Comparison of the Shear Bond Strength Between Metallic Orthodontic Brackets and Different Porcelain Surface Preparations

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a été évalué par un jury composé des personnes suivantes:

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Résumé

Introduction : La force d'adhésion à l'interface métal-céramique avec les résines auto-polymérisantes destinées au collage indirect des boîtiers orthodontiques n'a pas été évaluée à ce jour et un protocole clinique basé sur la littérature scientifique est inexistant.
Objectifs : 1) Comparer la force de cisaillement maximale entre des boîtiers métalliques et des surfaces en porcelaine préparées selon différentes méthodes; 2) Suggérer un protocole clinique efficace et prévisible.
Matériel et méthodes : Quatre-vingt-dix disques en leucite (6 groupes; n = 15/groupe) ont été préparés selon 6 combinaisons de traitements de surface : mécaniques (+ / - fraisage pour créer les rugosités) et chimiques (acide fluorhydrique, apprêt, silane). Des bases en résine composite Transbond XT (3M Unitek, Monrovia, California) faites sur mesure ont été collées avec le système de résine adhésive auto-polymérisante Sondhi A + B Rapid Set (3M Unitek, Monrovia, California). Les échantillons ont été préservés (H_2O/24hrs), thermocyclés (500 cycles) et testés en cisaillement (Instron, Norwood, Massachusetts). Des mesures d'Index d'adhésif résiduel (IAR) ont été compilées. Des tests ANOVAs ont été réalisés sur les rangs étant donné que les données suivaient une distribution anormale et ont été ajustés selon Tukey. Un Kruskall-Wallis, U-Mann Whitney par comparaison pairée et une analyse de Weibull ont aussi été réalisés.
Résultats : Les médianes des groupes varient entre 17.0 MPa (- fraisage + acide fluorhydrique) à 26.7 MPa (- fraisage + acide fluorhydrique + silane). Le fraisage en surface ne semble pas affecter l'adhésion. La combinaison chimique (- fraisage + silane + apprêt) a démontré des forces de cisaillement significativement plus élevées que le traitement avec (- fraisage + acide fluorhydrique), $p<0,05$, tout en possédant des forces similaires au protocole typiquement suggéré à l'acide fluorhydrique suivi d'une application de silane, l'équivalence de (- fraisage + acide fluorhydrique + silane). Les mesures d'IAR sont significativement plus basses dans le groupe (- fraisage + acide fluorhydrique) en comparaison avec celles des 5 autres groupes, avec $p<0,05$. Malheureusement, ces 5 groupes ont des taux de fracture élévés de 80 à 100% suite à la décimentation des boîtiers.
Conclusion : Toutes les combinaisons de traitement de surface testées offrent une force d'adhésion cliniquement suffisante pour accomplir les mouvements dentaires en orthodontie. Une application de silane suivie d'un apprêt est forte intéressante, car elle est simple à appliquer cliniquement tout en permettant une excellente adhésion. Il faut cependant avertir les patients qu'il y a un risque de fracture des restorations en céramique lorsque vient le moment d'enlever les broches. Si la priorité est de diminuer le risque d'endommager la porcelaine, un mordançage seul à l'acide hydrofluorique sera suffisant.

Mots-clés : Porcelaine, céramique, surface de préparation, collage indirect, Sondhi, boîtier métallique, orthodontie

Abstract

Background : Bond strength at the metal-ceramic interface of auto-polymerizing resins used in orthodontic indirect bonding has not yet been evaluated and a literature-based clinical protocol is lacking.
Goals : 1) To compare shear bond strength (SBS) between metal brackets and differently treated porcelain surfaces; 2) To suggest efficient and predictable chairside approaches.
Materials and methods : Ninety leucite discs (6 groups; n=15/group) were prepared following 6 combinations of mechanical (+/- bur roughening) and chemical (hydrofluoric acid, primer, silane) treatments. Metal brackets with custom composite resin Transbond XT (3M Unitek, Monrovia, California) bases were bonded with the adhesive resin system Sondhi A+B Rapid Set (3M Unitek, Monrovia, California). Samples were stored (H_2O/24hrs), thermocycled (500 cycles) and tested (Instron, Norwood, Massachusetts). Maximum SBS and adhesive remnant index (ARI) scores were collected for each sample. ANOVAs were performed on ranks since data was not normally distributed, and then adjusted with the post-hoc Tukey method. A Kruskall-Wallis, a Mann Whitney U pairwise comparison and a Weibull analysis were also performed.
Results : SBS medians of groups ranged from 17.0 MPa (- bur + hydrofluoric acid) to 26.7MPa (- bur + hydrofluoric acid + silane). Bur roughening did not affect bond strength. The chemical preparation of (- bur + primer + silane) showed statistically significant higher SBS than (- bur + hydrofluoric acid) preparation ($p<0,05$), while having similar SBS to the popular recommended protocol (- bur + hydrofluoric acid + silane). ARI scores were statistically significant lower in group (- bur + hydrofluoric acid) with $p<0,05$, while all other 5 groups were not different from each other. Percentage of porcelain damage in these 5 groups were very high at 80-100%.
Conclusion : All the tested surface preparations combinations provided clinically adequate adhesion for orthodontic tooth movement. A silane and primer combination for porcelain surface preparation is clinically attractive as it is safe and simple and provides great adhesion for orthodontic tooth movement. It is wise to warn patients that there is a risk of porcelain fractures when debonding brackets. If one prefers to avoid porcelain fracture at all cost, one may treat porcelain with hydrofluoric acid only.

Keywords: Porcelain, Ceramic, Surface preparation, Indirect bonding, Sondhi, Metal bracket, Orthodontic

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Terminology

Adhesion : The property of remaining in close proximity, as that resulting from the physical attraction of molecules to a substance or molecular attraction existing between the surfaces of bodies in contact.[1]

Bond strength: The force required to break a bonded assembly with failure occuring in or near the adhesive/adherens interface. Bond force is divided by the area of the bonded interface. The units of bond strength are megapascals (MPa), kilograms per square centimeter (kg/cm^2), and pounds per square inch (lb/in^2 or psi). It is common to see *bond force* reported with units of Newtons (N), kilograms (kg), or pounds (lb).[1, 2]

Bonding : Joining together secure with an adhesive substance such as cement or glue; the procedure of using an adhesive, cementing material or fusible ingredient to combine, unite or strengthen; an adhesive technique in dentistry involving conditioning of a surface as to create tags in the stucture for mechanical retention of a restorative material.[1]

Ceramics : Compounds of one or more metals with a non-metallic element, usually oxygen, and non-metal mineral, as clay. They are formed of chemically and biochemically stable substances that are strong, hard, brittle and inert non-conductors for thermal and electrical energy.[1]

Cement: Dental cements consist of an acid component and an alkaline component that, when combined, result in the hardening or setting of the mixture via a neutralization reaction. Cements are brittle, with relatively high compressive strength, low tensile strength, and relatively low fracture resistance.[3]

Glass Ionomer Cement : The conventional, chemically-cured glass ionomer cement (GIC) is supplied as a powder and liquid that are either mixed by hand or are encapsulated for automatic mixing. The powder is a calcium fluoroaluminosilicate glass, and the liquid is typically a solution of a polyacrylic acid copolymer in water.[2]

Resin-Modified Glass Ionomer Cement : The orthodontic use of GICs increased dramatically with the development of resin-modified GICs (RMGIC). The addition of 10-20% resin monomers to the GICs resulted in a cement that is initially hardened with the use of either light or chemical activators to polymerize the monomers. RMGICs are adhesive cements with improved physical properties and more stable hydrogels compared with GICs. Capsulation of RMGIC powder and liquid components simplified mixing procedures with a triturator.[3]

Hybrid Ionomer : These materials are also known as light-cured glass ionomers and resin-modified glass ionomers. They are supplied as a powder and liquid that are mixed by hand. The powder is typically a fluoroaluminosilicate glass. The liquid is a complex monomer containing carboxylic acid groups that react with the glass and tooth structure, and vinyl groups that can polymerize once they are chemically- or light-activated.[2]

Resins: A broad term used to describe natural or synthetic substances that form plastic materials after polymerization. They are named according to their chemical composition, physical structure, and means for activation of polymerization. They can be either light-activated, chemically-activated, or dual-cured with combined light- and chemical-activation.[1, 3]

Composite Resin: This material is formulated from glass particles and dimethacrylate monomers. The highly filled resin composites contain 60-80% by weight of glass filler, whereas the lightly filled composites contain about 28% by weight of silica.[2]

Adhesive resin : Any resin material with incorporated adhesive chemicals such as organophosphates, HEMA (hydroxyethyl methacrylate), or 4-META (4 methacrylethyl trimellitic anhydride) ; in dentistry, it describes the luting agents used with resin bonded prosthesis.[1]

Silane : This coupling agent is used to enhance bond strength to porcelain surfaces by chemical adhesion. Silanes are difunctional molecules, with one region compatible to bond with the silica within the porcelain, and the other having a -C=C group that cross-polymerizes with the bonding resin, thus forming a bridge between the two materials.[4]

List of Abreviations

Al_2O_3 : Aluminium oxide or alumina

APC: Adhesive pre-applied composite resin to bracket system

APF : Acidulated phosphate fluoride

ARI : Adhesive remnant index

CO_2 : Carbon dioxide

GICs : Glass ionomer cements

HFA : Hydrofluoric acid

PA : Phosphoric acid

ISO : International organisation for standardization

MC : Maximum cure

MPa : Mega Pascals

N : Newtons

OTM : Orthodontic tooth movement

RMGIC : Resin-modified glass ionomer cement

SBS : Shear bond strength

SD : Sondhi Rapid Set A+ B Indirect Bonding system, adhesive resin

SEM : Scanning electon microscopy

TXT : Transbond XT, composite resin

YAG : Yittrium aluminium garnet

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To my loving parents for coming to Canada without a penny, for all the sacrifices they have made for us and their future generations. To my husband Steve and my brother Alex who have always been unmistakably there for me.

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1. INTRODUCTION

Orthodontics has its roots from the Greek word *orthos*, which means *straight* or *proper* or even *perfect*. Orthodontics is the specialty of dental medicine which focuses on the malalignment of the teeth and of the jaws. A typical comprehensive orthodontic treatment requires application of forces to generate orthodontic tooth movements (OTM) in order to displace and align teeth. OTM can be performed with removable appliances, but also by cementing fixed appliances such as bands or brackets on the tooth. OTM is only generated once wires are inserted into the appliances' slots. The bonding of orthodontic brackets for the entire duration of the orthodontic treatment is a very common procedure.

Bonding in orthodontics is semi-permanent in that bond strength of orthodontic attachments should be high enough to resist accidental debonding during treatment, but also low enough to facilitate the debond of brackets with light forces at the end of the treatment and not damage the tooth surfaces. Brackets can be attached on dental surfaces by two methods: direct bonding, which is performed chairside; or indirect bonding, which involves an additional laboratory step before the chairside step.

The method for direct bonding of orthodontic brackets is well known and understood by clinicians. It begins with the isolation of the oral environment, preparation of the tooth surface, application of uncured composite resin on the back of the bracket, and placement of the individual bracket onto the tooth surface. Photo-polymerization of the composite resin is initiated once ideal bracket position is obtained, as shown in Figure 1. Ideally this step is performed on each tooth individually.

Figure 1: Direct bonding method of individual brackets performed chairside. (All images adapted from http://www.drbiteright.com/gettingbraces.htm)

The ideal placement of brackets is critical to effectively meet treatment plan objectives. The brackets fulfill essential orthodontic goals such as the leveling of the marginal ridges, which in return level the cenamo-enamel junction and consequently the bone levels. Bone levels tend to be parallel to the cemento-enamel junction in healthy periodontium. Bracket placement can also meet various treatment objectives such as vertical control to maintain a Curve of Spee and prevent auto-rotation of the mandible, or more gingival placement of incisor brackets to close a dental openbite. Hence, over-corrections are easy to incorporate with brackets.[5]

However, the placement of brackets can be challenging as orthodontists have come to recognize some of the generic problems associated with the direct bonding technique. First, there is difficulty in visualizing the intra-oral vertical and horizontal planes of moderately to severe malpositioned teeth. Secondly, access may be limited and this can frequently lead to a less than ideal bracket placement position. Clinician fatigue during a comprehensive bonding session and patient comfort are other problems associated with direct bonding.[6] In a previous direct bonding failure rate study, a higher bonding failure rate in the posterior region was detected. This high failure rate may be related to the increased difficulty of isolation against saliva and humidity in the posterior segments of the mouth.[7]

Indirect bonding method of brackets was developed to overcome the difficulties associated with the direct bonding technique. The first indirect bonding technique was introduced and published in 1972.[8] The proposed method is divided into two stages: the laboratory step and the clinical procedure. Brackets are placed on stone models in the lab, allowing orthodontists to visualize teeth and brackets easily from all angles, before transfering them to the mouth as shown in Figure 2. By facilitating ideal bracket positioning, this approach might decrease the need to reposition brackets during the course of the treatment. This method will be explained in greater depth in the later sections.

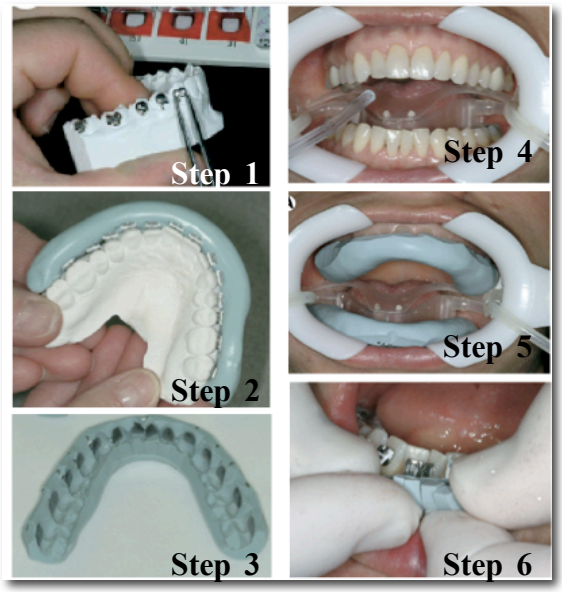


Figure 2: Two-step procedure for the indirect bonding method. Left images : represent the laboratory steps 1, 2 and 3; Right images : represent the chairside steps 4, 5 and 6. (All images adapted from Kalange[9])

Two problems quickly arose with the indirect bonding method. First, the resin systems originally designed for the direct bonding method were tried in the indirect method but resulted in disappointment. Research and development for an adhesive resin suitable for the indirect bonding method thus began. Initially, there were higher bond failures rates with the first few indirect bonding products, off-setting the advantages of the method.[10] With time, the protocols and products have improved greatly.[5, 9, 11-14]

The stepping stone occured in 1999, when a new indirect bonding method developped by Dr. Anoop Sondhi and 3M Unitek entered the orthodontic market. The Sonhdi Rapid Set A+B adhesive resin system (3M Unitek, Monrovia, California) is an auto-polymerizing resin with faster cure times and leaves minimal adhesive resin flash around brackets after tray removal in comparison with the other competitors' products.[15] Since then, the indirect bonding method has gained popularity. A survey in 2009 revealed that 46% of the orthodontic residents in North America plan to use the indirect bonding methods in private practice.[16] Today, clinical failure rates of indirect bonding are similar to those of direct bonding.[17]

Many modern orthodontic appliances are currently being manufactured to high precision using sophisticated computer-aided designs and robotic machines. Each tooth has its specific bracket with tip and torque prescriptions incorporated in the slot, allowing ideal alignment within the arch. To take full advantage of the precision built into these appliances, an equally precise method for bonding them to the tooth surfaces is required.[9] Hence, with the increased use of prescription bracket appliances, clinicians will place a greater emphasis on the ideal and exact positioning of brackets, and the indirect bonding technique may become even more popular.[7]

However, new problems have arisen as an increasing number of adult patients are seeking orthodontic treatment. The increased demand among adults for orthodontic treatment generally leads to more frequent bonding of orthodontic attachments to various non-enamel surfaces, such as composite or porcelain substrates. Unlike with composite surfaces, a lack of durable bonding forces between brackets and ceramic restorations unfortunately persists in clinical orthodontics, whether with direct or indirect bonding methods.[9]

This thesis will focus on finding a predictable porcelain surface preparation for clinicians who plan to use the indirect bonding method and its related products.

2. LITERATURE REVIEW

2.1 The Indirect Bonding Technique

The original indirect bonding technique recommended placing orthodontic brackets on plaster models using sugar candy. The brackets were transfered to the mouth through a transfer tray which was like an arch-long mouthguard. The candy was removed and replaced by a composite resin or cement at the time of the chairside bracket delivery. Therefore custom bases were made chairside. This original method had many problems because it left excessive amounts of composite resin flash, which was very time-consuming to remove.[12]

Authors then suggested modifications to the indirect bonding technique with laboratory made custom composite bases. In 1979, Thomas revolutionized the indirect bonding protocol by making the custom bases in the laboratory, instead of chairside. He eliminated the sugar candy, immediately applied filled composite on the bracket bases, and then placed them directly on the model casts. Once bracket positions were approved, they were cured and then transfered to the mouth with a transfer tray.[11]

The indirect bonding method of orthodontic brackets can be generally divided into a laboratory step and a chairside step. No bands are typically used in the technique; however, if a case requires bands for a transpalatal arch, it can be bonded directly chairside.[5, 14, 18] Each manufacturer can occasionally suggest their own variation of the laboratory or chairside step.

When comparing direct and indirect bonding, the underlining principles are the same: the bases are said to be "custom" because they are adapted to each individual tooth's anatomy and position in the three planes. However, the difference is that custom bases in the indirect bonding method are fabricated on a stone model in the laboratory, whereas in the direct bonding technique the custom bases are made chairside, intra-orally, directly on the patient's teeth.

2.1.1 Essential Steps of Indirect Bonding Brackets

1) Chairside appointment

Impressions for model cast fabrication:

Tooth surfaces are cleaned with pumice. Accurate impressions are taken with mechanically mixed alginate and metal impression trays. Accurate impressions are essential since the reference for bracket placement is the incisal edge and the marginal ridges.[18] In cases that require tooth recontouring, some authors recommend that it be done before impressions are taken so that overall accuracy can be maximized.[9, 14] For adults with mature dentitions, a two-week interval has clinically shown to be acceptable. However, the recommended time interval between the impression appointment and the bonding appointment is limited to 10 days for adolescents. Small eruptive movements of the teeth can become significant if there is a longer delay between the appointments, especially in growing patients. Significant tooth eruptions can cause transfer trays to fit imprecisely, leading in reduced bracket placement accuracy.

2) Laboratory steps

Cast model preparation:

The laboratory technique begins by pouring the stone model or working cast in dental stone from the acurate impressions. As depicted in Figure 3, green and pink stone are commonly used as they are precise, dimensionally stable, and replicate details well. Casts should be distortion- and bubble-free. The casts are then trimmed and allowed to dry completely.[9]

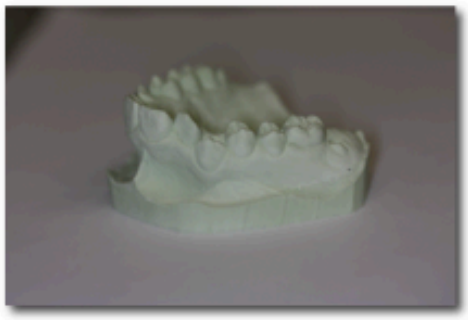


Figure 3: Individual cast in green stone.
(Image courtesy of Dr. Stephanie H. Mai, Université de Montréal)

Bracket placement and custom base fabrication:

On the dry stone model, reference lines are added to assist in bracket placement (Figure 4). Vertical lines represent the long axis of the teeth, and horizontal lines represent the marginal ridge lines. Some clinicians also add a third line that represents the slot line.[14] A caliper may be used to increase precision. Placing these lines on the working casts ensures a customized bracket prescription placement for each patient. The stone model teeth are then painted with a thin coat of separating medium and allowed to dry.

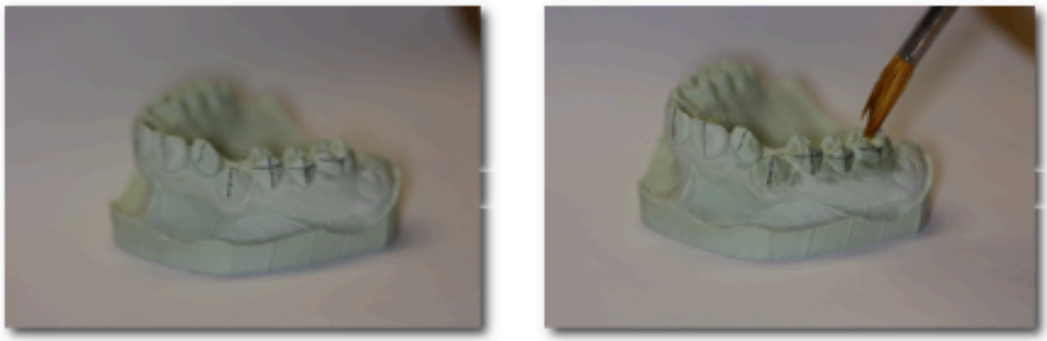


Figure 4: Left image : Reference lines for bracket placement ;
Right image : application of the separating medium.
(Images courtesy of Dr. Stephanie H. Mai, Université de Montréal)

Composite resin is applied to the bracket's base. Brackets are then placed on the casts and, once brackets positions are considered ideal, the composite resin can be cured according to the manufacturer's recommendations, as depicted in Figure 5.[14]

Figure 5: Once brackets are placed and attached to the stone cast, polymerization of custom composite resin bases is done in a light curing unit, for 10 minutes. (Images courtesy of Dr. Stephanie H. Mai, Université de Montréal)

Transfer tray fabrication:

Once the custom bases are cured, these ideal bracket placements are recorded with a tray for each dental arch. Trays can be made of silicone, thermal glue, polyvinylsiloxane (Figure 6) or polyvinyl stock papers under vacuum, and can be transparent or colored.[19] Regardless of the transfer tray material, it is important to adapt the material over the incisal edges and occlusal surfaces of the teeth. This creates an index for accurate tray seating intra-orally during chairside bracket delivery.

Tray fabrication is a technically sensitive step as an inadequate tray can prevent proper tray seating, introduce inaccuracies, and result in bond failure by uneven adhesive resin distribution or saliva contamination. The tray should be about 5 mm thick to provide enough bulk for support and rigidity. If the tray is too thin, it will be flexible and may distort because of the finger pressure during delivery. If the tray is too thick, it may be

difficult to fully seat it and can be combersome for the patient.

Some authors also recommend using an additional shell to support the transfer trays, called the the "outer-tray". The "outer-tray" can be fabricated either with a 0.020 inch vacuum-form clear Essix (Dentsply Raintree Essix, Sarasota, Florida) or with a cold acrylic material that covers the polysiloxane or silicone " inner-tray ". These " outer-trays " are accurate, stable and compact (Figure 7).[6, 19]

Figure 6: " Inner " transfer tray fabrication with light polyvinylsiloxane and putty. (Images courtesy of Dr. Stephanie H. Mai, Université de Montréal)

Once the trays have been fabricated, they are detached from the casts by soaking in a water bath for at least 30 minutes or until no more air bubbles rise from the models. After soaking, trays are carefully separated from the models using light finger pressure. The brackets will remain embedded inside the transfer trays. If a light-cured or dual-cured composite resin was used, the bracket bases need to be cured again to ensure complete polymerization in their center.

Trays are trimmed to prepare them for bracket delivery: the trays can be carefully trimmed to expose the gingival edge of the bracket bases, allowing for excess adhesive resin to seep out during bonding. It is important to leave the tray material covering the entire occlusal and incisal surface and part of the lingual surface of the teeth to provide an index for accurate tray seating.

Figure 7: Left image : polymerized " inner " transfer tray separated from stone cast ; other images: cold-cured acrylic " outer " transfer tray on top of " inner " tray. (Images courtesy of Dr. Stephanie H. Mai, Université de Montréal)

Transfer trays can be separated into quadrants by sectioning them at the midline allowing easier seating and removal in comparison to a full arch tray. Trimming at the midline also provides a visual verification for full seating of the transfer trays.[9]

Pre-delivery preparation of the composite bases :

A residual film of separating medium or stone may still be present on the custom composite resin bases. While the brackets are still encased in the transfer tray, their bases are cleaned with a micro-etch and 50 μm aluminum oxide (Al_2O_3), then rinsed with distilled water, and dried with forced air.[9] Some authors even recommend cleaning with soap.[19] The trays are then stored away from contaminants until the patient returns for the bracket delivery appointment.

3) Chairside steps:

Bracket bonding delivery and arch wire engagement

Before isolating the mouth, the teeth should be cleaned with a fluoride-free pumice. The Nola Dry Field System (Nola Specialties Inc, Covington, Louisiana) can be useful for isolation. The teeth are etched with a 37% phosphoric acid (H_3PO_4) solution or gel for 30 seconds, then rinsed thoroughly and dried. An indirect bonding adhesive resin system can

now be applied to the bracket bases and on the teeth with a microbrush. Since there is a greater risk of saliva accumulation in the posterior segments throughout the appointment, distal teeth are idealy painted first with the microbrush to prevent cross-contamination with other teeth.[9]

The adhesive resin used for the bracket delivery can be light-cured or chemically-cured, the latter being the most common. In a chemically-cured adhesive resin system, a thin layer of component A is painted on the tooth and component B on the bracket bases with separate microbrushes. The polymerization reaction will start when the two components are brought in contact. Trays are then placed and held in mouth with a light finger pressure for the recommended time to allow complete polymerisation of the adhesive resin (Figure 8). Trays need to be removed carefully to avoid accidental bracket debonding. If a bracket fails after removal of the transfer trays, it can be rebonded directly.

Figure 8: Nola System installation and transfer tray for upper arch seated in mouth for polymerization after application of the chemically-cured adhesive system Sondhi Rapid Set in which component A is applied on teeth and component B is applied on custom composite resin bases.
(Image courtesy of Dr. Stephanie H. Mai, Université de Montréal)

As the custom bracket bases have an intimate fit against the tooth surface, excess adhesive resin application should be avoided, and be removed with a scaler. Archwires are placed in the usual manner immediately after clean up.[9] Typically, one hour is scheduled

to perform indirect bonding of both arches, to engage initial archwires, and to review instructions with the patient and the parents.

Since the chairside steps do not require any handpieces or any particular orthodontic knowledge, a trained hygienist in many instances will be performing this chairside step. This allows the orthodontist to be free to attend other patient needs.

2.1.2 Advantages of the Indirect Bonding Method

Thomas et al. initially published an extensive list of advantages for the indirect method (Appendix 1). However, subsequent studies showed that several of these advantages were unsupported by the literature. Today, advantages for the indirect bonding technique include decreased chair time, less patient discomfort, easier debonding, and improved ability to bond posterior teeth.[20] As brackets are placed in the laboratory, it has been suggested that indirect bonding results in more accurate bracket positioning. When comparing direct and indirect bonding, Koo et al. found that indirect bonding resulted in more accurate height of bracket placement, but did not note a difference in angulation or mesiodistal bracket position.[21] Along with other authors, Aguirre et al. demonstrated that neither direct nor indirect bonding techniques resulted in 100% accuracy of bracket positioning.[20-22]

The other clear advantage of the indirect bonding method is the efficient usage of the orthodontist and the staff's office time. Clinicians may use any free time during the day to complete the steps of the indirect bonding method. Additionally, small tasks, like the fabrication of transfer trays and preliminary bracket positioning on model casts can be delegated to auxiliary personnel.[14] As noted above, the chairside indirect bonding of orthodontic brackets via transfer tray can be performed by a trained hygienist, freeing the orthodontist's time further.

The general perception is that direct bonding is physically and mentally demanding. With indirect bonding, there is no pressure on the clinician to make crucial bracket placement decisions in a less-than-ideal working field, with limited access and visibility. The indirect bonding method is more ergonomic as the delivery of the brackets is faster than bonding individual brackets and access is less of an issue. As a result of shorter appointments, patients can benefit from this overall more comfortable experience.[5] If patients go through a more comfortable experience, they will have a greater attention span for the delivery of instructions and can benefit from more time for routine questions at the end of the bracket delivery appointment.[18]

Some authors also argue that the indirect bonding method is more efficient and more profitable: a study by Keim et al. found that practices with higher gross income typically used indirect bonding.[23]

Table 1 shows a revised list of advantages for the indirect bonding method, based on recent publications mentionned above.

Table 1: Revised advantages for the indirect bonding method.[20]

Advantages for the orthodontist	Advantages for the patient
1. Decreased chair time 2. Improved ability to bond posteriors 3. Enhanced accurate bracket positioning 4. Less physically and mentally demanding bonding appointment 5. Some steps can be delegated to auxiliary personnel 6. Make good use of office " downtime " 7. Increased general office efficency 8. Potential increase in profit	1. Less patient discomfort 2. Shorter bonding duration 3. More time remaining for question period at the end of the bracket delivery appointment.

2.1.3 Disadvantages of the Indirect Bonding Method

There are two main disadvantages to the indirect bonding method. First, it is generally more technique sensitive, where errors can be incorporated at each step, and can be compounded with each subsequent step. Secondly, the method requires significantly greater laboratory preparation time and costly materials.

Impressions and models must be accurate and transfer trays must be properly fabricated. In a clinical setting, incorrect placement of a tray for multiple teeth may result in larger adhesive resin film thickness, decreased bracket bond strength, and inaccurate placement of brackets.[20]

Ciuffolo et al. highlight three critical steps where indirect bonding is especially technique sensitive: impression, adhesive resin application, and transfer tray (fabrication, application and removal). Of these steps, transfer tray stability and its ease of removal is the most important as accidental debonding and failures easily occur.[19]

Dheal et al. found that the modest increase in bracket placement accurary for individual tooth might not necessarily lead to a clinically significant difference for the patient in terms of treatment time or number of visits, as it was initially aspired to grant.[17]

At an organizational level, orthodontists who decide to implement the indirect bonding method in the clinic should set up their clinics to mainly follow the indirect bonding protocol. This allows staff to develop routines for tasks, to manage emergencies efficiently, and to avoid technique sensitive errors due to lack of practice and familiarity.

2.2 Types of porcelain

Ceramic material is believed to give the most esthetically pleasing option for the replacement of a lost tooth, the repair of a damaged tooth, or for masking an unattractive enamel surface. The demand for better restorations has led to the development of more advanced porcelain systems.

Ceramics are made from the melting and fusion of non-metallic minerals, like clay, after having fired them at high temperatures (850-13,000º Celsius). Dental porcelains are a form of ceramic, and can be classified according to:

1. Indications: anterior, posterior, crowns, veneers, post and cores, stain ceramics, glaze ceramic and fixed partial dentures (bridges)
2. Composition: pure alumina, alumina-based glass ceramic, pure zirconia, zirconia-based glass ceramic, silica glass ceramic, leucite-based glass ceramic and lithia-based glass ceramic
3. Processing methods: sintering, partial sintering and glass infiltration, copy-milling and CAD-CAM
4. Firing temperature: ultra-low fusing, low-fusing, medium-fusing and high-fusing
5. Microstructure: glass, crystalline, and crystal-containing glass
6. Translucency: opaque, translucent and transparent
7. Fracture resistance
8. Abrasiveness

For the purpose of this thesis, a general understanding of the various dental ceramics currently available will aid in understanding the materials' different behaviors. There are essentially two families of dental porcelains: the family of glass ceramics and the family of poly-crystalline ceramics in which physical properties vary greatly (Figure 9 and

Figure 10). Table 2 states physical properties of all-ceramic ingots or discs in regards to their indications and ease of bonding to orthodontic brackets.

Figure 9: Samples of popular all-ceramic dental products
A : IPS Empress ingots (Image adapted from http://www.dentalcadcam.de); B : In-Ceram ingots (Image adapted from www.vita-zahnfabrik.com); C : Finesse All-Ceramic ingots (Image courtesy of Dr. Stephanie H. Mai, Université de Montréal)

The family of glass ceramics can further be divided into three sub-groups of dental ceramics: feldspathic porcelain, leucite-reinforced porcelain and lithium-disilicate porcelain. Feldspathic porcelain is formed from clay or sand that has been fired at high temperatures. It becomes a vitreous dental ceramic formed of a glass matrix and one or more crystalline phases. Conventional dental feldspar porcelains contain a silica network (SiO_2, 52-62% by weight), alumina (Al_2O_3, 11-16% by weight), lithium oxide and barium oxide additives, and either potash (K_2O, 9-11% by weight), soda (Na_2O, 5-7% by weight) or both. As dental feldspars are relatively colorless and pure, pigments, opacifiers and other types of glass modifiers are required to reproduce the hues of natural teeth, to control the fusion and sintering temperatures, and to control the coefficient of thermal contraction and solubility.[4]

Feldspathic porcelains are the most esthetic type of porcelain, but have the weakest flexural strength of 90 MPa; they contain less than 40% leucite by content. Leucite is a crystalline mineral formed from melting potassium feldspar or potash. In other words, leucite is a potassium-aluminum-silicate mineral.[24] In contrast, leucite-reinforced or leucite-based glass ceramics contain more than 35-50% of leucite in weight dispersed in a

glassy matrix, and have a higher flexural strength of 110 MPa.[25] Lithium-disilicate or lithia-based glass ceramic has a greater flexural strength of 300-400 MPa. These materials can be relatively translucent.[26]

The family of poly-crystalline ceramics is divided into two sub-groups: alumina or zirconia ceramics. The alumina or zirconia may come in pure forms, or be dispersed in a glass matrix as alumina- or zirconia-based glass ceramic. Alumina ceramics have a high fracture toughness and hardness, with a flexural strength of 700-800 MPa. It is often used as a porcelain core upon which esthetic feldspathic ceramics can be layered.[24]

Zirconia or zirconium oxide is also considered a core material as it has the highest flexural strength of 1100-1300 MPa. Although this type of ceramic is the strongest and toughest, it has disadvantages: zirconia can only be fabricated through computer aided design-computer aided manufacturing (CAD-CAM) technology, which can be expensive and technique sensitive; zirconia ceramics are also commonly limited to posterior crowns or fixed-partial dentures due to its greater opacity.[24] Furthermore, bonding to zirconia is extremely challenging as it contains little or no glass matrix required for etching and silane conditioning. For example, In-Ceram Zirconia is 30 % zirconia and 70 % alumina by weight.[4]

Comparison of Available All-ceramic Systems

Brand	Captek	Ceramco	Cerinate	Dicor MGC	Empress	Empress 2	Empress Cosmo	Finesse
Manufacturer	Precious Chemicals	Dentsply	Den-Mat	Dentsply	Ivoclar	Ivoclar	Ivoclar	Dentsply
Crystalline phase	Leucite	Leucite	Leucite	Tetrasilicic fluormica	Leucite	Lithium disilicate	Lithium phosphate	Leucite
Recommended usage	Crowns	Inlays Onlays Veneers	Inlays Onlays Crowns Veneers	Inlays Onlays	Inlays Onlays Crowns Veneers	3-unit FPDs Crowns	Endodontic foundation	Inlays Onlays Crowns Veneers
Fabrication	Metal core or sintered	Sintered	Sintered	CAD/CAM	Heat-pressed	Heat-pressed	Heat-pressed	Heat-pressed
Strength	Low	Low	Medium	High	Medium	High	Medium	Medium
Fracture toughness	Medium	Medium	Medium	Medium-high	Medium	High	Medium	Medium
Translucency	Opaque	Medium	Medium	Medium	Medium	Medium	Opaque	Medium
Enamel abrasiveness	Medium	Medium	High	Low	Medium	Low	*	Medium
Marginal fit	Good	Fair	Fair	Fair	Fair	Fair	*	*

*Not tested.

Comparison TABLE 25-1

Brand	Helioform	In-Ceram	In-Ceram Spinell	In-Ceram Zirconia	Mark II	Optimal	ProCad	Procera	Metal Ceramic
Manufacturer	Vident	Vident	Vident	Vident	Vident	Jeneric/ Pentron	Ivoclar	Nobel Biocare	Various
Crystalline phase	Leucite	Alumina	Alumina Spinel	Zirconia/ alumina	Feldspar	Leucite	Leucite	Alumina	Leucite
Recommended usage	Crowns	Crowns Veneers	Crowns Veneers	3-unit FPDs	Inlays Onlays Crowns	Inlays Onlays Crowns Veneers	Inlays Onlays Crowns	Crowns	Crowns FPDs
Fabrication	Electro-formed gold core or sintered	Slip-cast core or sintered	Slip-cast core or sintered	Slip-cast core or sintered	CAD/CAM	Heat pressed	CAD/CAM	CAD/CAM	Cast framework or sintered
Strength	Low	High	High	Very high	Medium	Medium	Medium	Very high	Very high
Fracture toughness	Medium	High	High	Very high	Medium	Medium	Medium	Very high	Medium
Translucency	Opaque	Opaque	Medium	Opaque	Medium	Medium		Opaque	Opaque
Enamel abrasiveness	Medium	High	High	High	Medium	Low	*	Medium	Medium
Marginal fit	Good	Fair	Fair	Fair	Fair	Fair	Fair	Fair	Good

Figure 10: Comparison of all-ceramic dental materials frequently used. Finesse All-ceramic by Dentsply, highlighted in red, is of particular interest for this Master's project. (Table adapted from Contemporary Fixed Prosthodontics.[24])

Table 2: Bonding properties of common ceramic ingots used in peer-reviewed literature.

Ingots	General Composition	Fabrication Process	Indications	Bonding Concerns
IPS Empress (Ivoclar-Vivadent, Amherst, New York) [4, 27]	Glass porcelain: feldspathic ingots made up of micro-leucite or lithium-disilicate crystals	Hot-pressed : Controlled crystallization in a glass containing nucleating agents. They are heated and subsequently pressed in a mould using an alumina plunger to form an all-ceramic restoration	- Veneers - Inlays - Onlays - Anterior crowns - Posterior crowns and fixed partial denture with IPS Empress 2	Bonding can be performed predictably via the glass particles.
In-Ceram (Vita Zahnfabrik, Bad Säckingen, Baden-Württemberg) [4, 27, 28].	Aluminus porcelain ; made with an aluminium oxide infiltrated core	Slip cast : Infiltrated molten glass matrix with a porous core made out of aluminum oxide subsequently veneered with feldspathic porcelain. Considered the strongest among all-ceramic restoration	- Anterior crowns with In-Ceram Spinell and In-Ceram Alumina. - Posterior and anterior fixed partial dentures with In-Ceram Alumina. - Any posterior restaurations with In-Ceram Zirconia.	Surfaces are more homogeneous and thus less susceptible to acid etching. Etched with boiling sulfuric acid is possible, a procedure that is inapplicable in orthodontics.
Y-TPZ [26, 29, 30].	Yttria-stabilized polycrystalline tetragonal zirconia : tetragonal phase of zirconia is stabilized at room temperatue with Y_2O_3	Direct sintering of crystals together without any matrix to form a dense, air-free, polycrystalline structure. It is a monophase ceramic.	Initially used in orthopedics, being bio-compatible. Recently used for endodontic dowels and implant abutments. An alternative core material and fixed partial dentures.	Far more homogeneous and not susceptible to acid etching or other mechanical forms of roughening.
Finesse All-Ceramic (Dentsply GAC, Bohemia, New York) [4, 31]	Leucite-reinforced pressable glass ceramic	Hot-pressed : fabricated via lost-wax injection moulding, low fusion (see IPS Empress)	- Single anterior crowns - Veneers - Inlays - Onlays	To date, no study has tested shear bond using the Finesse All-ceramic ingots.

2.3 Methods for Porcelain Surface Preparation

Ceramic is an inert material which does not adhere chemically to any of the currently available bonding resins. Therefore it is necessary to change the inert characteristics of the surface to achieve clinically acceptable bonding of brackets to porcelain surfaces.[27] Although commercially available porcelains are usually similar in chemical formula, they do have their own characteristics, and adhesion can vary as shown in Table 2.

Successful bonding depends on establishing a surface with a high population of unreacted vinyl groups (–C=C) that can then be cross-polymerized to the composite resin. Authors have suggested three different approaches: 1) physical or mechanical preparation, 2) chemical preparation and 3) combined mechanical and cheminal preparations of the porcelain.[29] The approaches will be discussed in depth in the following sections.

Insight into how to bond to ceramics can be obtained from literature on porcelain repair. The following treatments are cited by manufacturers of porcelain repair kits: micro-mechanical roughening with a diamond bur; air abrasion with 50 μm Al_2O_3; or etching with either 9.6% hydrofluoric acid (HFA) or 1.23% acidulated phosphate fluoride (APF). Mair et al. explains that these agents roughen the porcelain and provide physical or mechanical retention : the applied adhesive resin penetrate and become micro-mechanically locked, in a similar fashion as to the microtags formed in etched enamel.[29]

2.3.1 Mechanical Preparation

Mechanically preparing the porcelain involves the removal of the porcelain's glaze and/or the roughening of the porcelain to provide more surface area for mechanical retention. Several options are available and are relatively quick chairside procedures.

The use of coarse and fine diamond burs has been well documented, along with green stones, and abrasive disks.[32-34] Zachrisson et al. found that intra-oral sandblasting with microscopic particles of aluminium oxide removes the glaze better than burs or stones, since only a small amount of surface is removed and the result is more uniform.[35] Although this requires minimal chairside set-up, the aluminium oxide particles are difficult to contain within limits of the mouth and also requires thorough rinsing afterwards. Authors have found that fine diamond roughening and sandblasting showed the highest surface roughness when compared to surface roughness obtained by acid etching.[36]

A retention cavity can also be cut in the porcelain surface.[34, 37] One may not need to go as far as to creating cuts, as resin tag length is not a determinant of bond strength according to Eliades et al.[38] Laser radiation of the porcelain surface has been studied as an alternative conditioning technique, but it is a very costy procedure.[35]

2.3.2 Chemical Preparation

2.3.2.1 Acid Etching

The acid is meant to create a series of micro-retention pits by preferential dissolution of the glass phase within the ceramic matrix.[34] Although this procedure yields mecanical retention and not a chemical bond to the porcelain, it is included as part of a chemical preparation because it entails the application of a technique-sensitive liquid product. For chemical conditioning, HFA and APF can be used. The etch must be left on the porcelain surface, usually for more than 1 minute before rinsing, and caution is always taken to protect the patient and staff while using these acids.

Further understanding of HFA use can be found in restorative and esthetic dentistry because bonding of porcelain materials are common trade. Borges et al. have noticed that HFA application forms a honeycomb-like topography on the porcelain, ideal for micro-mechanical retention and bonding.[39] Etching protocols can also vary depending on the

type of ceramic involved. When treating feldspathic porcelain, restorative researchers recommend a 2-2.5 minute etching time with 9.6% HFA ; with leucite-reinforced ceramic, etching time with 9.6% HFA is of 60 seconds ; while with lithium disilicate ceramics, etching is only for 20 seconds.[40] Protocols would also vary should different acid concentrations be used.

Etching with HFA yields similar or even higher bond strengths than etched enamel. Strong acids such as 9.6% HFA have been used to increase bond strength of porcelain.[35] Clinicians must exercise caution during the intra-oral application of HFA, as soft tissue irritation and burns, or tooth damage, could result from accidental contact. HFA is highly toxic and corrosive. Soft-tissue barriers, like OpalDam (Ahren Dental, Stockholm, Stockholm) shown in Figure 11, are handy protective shields.[32, 33, 36]

Figure 11: OpalDam barrier for gingival protection from HFA
Black arrow pointing to the dam which is a light-cured resin applied with a seringe
(Image adapted from www.ahrendental.com)

Bourke et al. have questioned the clinical relevance of bond strengths with HFA application. His shear bond strength (SBS) study found that SBS was similar when comparing the groups that have used HFA with those that did not.[34] If there is no added advantage of using HFA, one should eliminate it for obvious reasons.

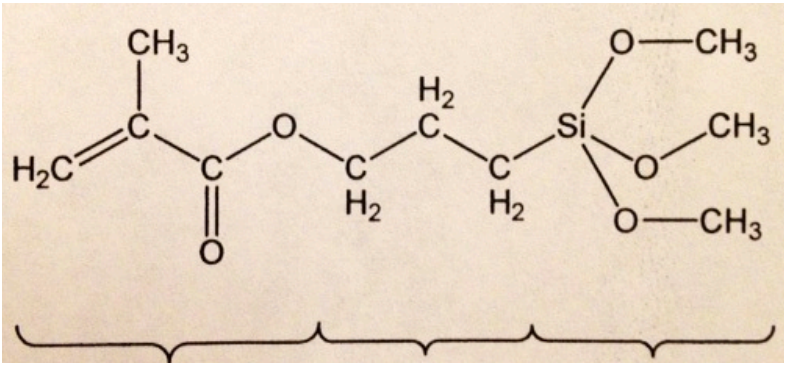
Another study found that 1.23% APF-etching was a suitable substitute to HFA etching, while being a safer product. A 10 minute etching time with APF provided similar SBS to a 1 minute HFA etching time.[27, 41] There are contradicting results in the current literature on APF application which provided clinically unacceptable low bond strengths.[27, 35, 42]

There are also inconsistent findings on the effect of conventional acid etching with phosphoric acid (PA) on porcelain bond strength. Some studies demonstrated that etching ceramic surfaces with 37% PA gave a clinically acceptable bond strength, comparable with the bond strength produced by the application of HFA, without silane application.[27, 33, 34, 43] However, Zachrisson et al. and Kocadereli et al. found that conventional acid etching was ineffective for mechanical retention of brackets to porcelain.[35, 44] Unlike HFA, 37 % PA does not actually etch porcelain nor produce topographical changes in the porcelain surface. It is hypothized that PA neutralizes the alkalinity of the adsorbed water layer, present on all intra-oral ceramic restorations. Therefore, PA can enhance the chemical activity of any silane primer that is subsequently applied.[34] Indeed, Larmour et al. found no statistically significant difference in bond strength between the HFA and PA etch technique, when followed by silane application.[33]

2.3.2.2 Silane Application

Silane is a coupling agent that can be used to enhance bond strength between inorganic porcelain surfaces and organic resin surfaces by chemical adhesion. Silanes are in fact difunctional molecules with an organic substrate and an inorganic subtrate. This coupling agent, also commonly refered to as the porcelain conditionner, displays the general chemical structure $R'—Si(OR)_3$, where R′ is the organofunctional group, typically an unsaturated methacrylate, that reacts to the adhesive system or the composite resin and creates a covalent bond by free radical polymerization. In the process of silanization, the alkyl group (R) is hydrolyzed to a silanol (SiOH), creating a covalent bond with the silicon

inorganic particles (Si—O—Si), thus completing the bonding process to the silica/glass matrix of the ceramic.[4] Hence, silane coupling agents provide a chemical interaction between the silicon-based ceramic and the carbon-based resin.[25] Silanization also increases the wettability of the ceramic surface.[32]



R' (Methacrylate group) **$(CH_2)_3$** **$Si(OR)_3$**

Figure 12: Silane molecule R'—$Si(OR)_3$
(Image adapted from Philipps' Dental Materials.[4])

Some studies reported a statistically significant increase in SBS after HFA and silane application. However Chung et al. cautioned the interpretation of these results because the choice of bonding agent has a significant impact on the SBS.[45] For example, glass ionomer cements (GIC) used for bonding generally have a weaker bond strength than composite resin. Cochran et al. and Kao et al. combined silane with GIC and demonstrated a statistically significant increase in SBS when compared with a control group using GIC only.[46, 47] On the other hand, the combination of silane with composite resin may not always significantly increase SBS because the SBS of compostite resin is already high. Some authors found similar SBS when HFA was followed with or without silane and use of composite resin in a clinical and *in vitro* studies.[32, 36, 48]

Whether the application of silane is recommended or not remains inconclusive because it is unclear if this additional step enhances SBS. On the other hand, Abu Alhajia et

al. view silane application as a substitute to mecanical preparation of the porcelain surfaces. Indeed, they have demonstrated that adequate bond strengths required for OTM can be achieved with conventional composite resins combined with silane application, without the need of any mechanical preparation. This alternative is interesting since mechanical preparation was associated with a higher incidence of porcelain fracture after debonding.[27, 47] Roughening introduces surface weaknesses or micro-cracks that can propagate into the porcelain body.[33, 47, 49] In the same line of thought, a few studies have in fact shown that bur roughening is unnecessary since it increases the bond strength beyond clinically acceptable values while risking unacceptable damage to the porcelain surface.[33, 49]

2.4 Concerns when Debonding

Cohesive failures occur either within the tooth substrate, the bracket or the adhesive system. Adhesive failures occur between the tooth-adhesive resin or bracket-adhesive resin interfaces. Unfortunately, cohesive fractures of ceramic restorations resulting from bracket removal are common and unpredictable. These fractures pose problems of esthetic and financial nature if they are large or extensively deep. The clinician may attempt to repair the slight porcelain damage with polishing systems. One can further try to prevent further extension of the micro-cracks by finishing and polishing with a series of graded ceramiste points or diamond-impregnated polishing wheels. Kao et al. and Wood et al. both agree that this procedure can yield an acceptable, although not ideal, esthetic result if finalized with a diamond polishing paste.[37, 47]

Understanding the nature of cohesive failures can give clues on how to avoid them. Cohesive porcelain fractures occur when the adhesive strength at the metal bracket-porcelain interface exceeds the cohesive strength of the porcelain. Mechanical roughening with diamond burs or sandblasting can be guilty of weakening the cohesive strength of the porcelain. Therefore, Wood et al. tried to avoid bur roughening and preserving the glaze.

He tested SBS on glazed and silanated porcelain. Unfortunatelly, this approach did not provide sufficient bond strength, so it was recommended that silane be combined with some form of mechanical retention treatment.[37] More recent studies, mentioned in the previous section, have found otherwise.[27, 47] However, there is a general concensus in the literature highly recommending a mechanical retention component when bonding to ceramics, as there will be greater potential of bracket failures mid-treatment of an orthodontic treatment and sub-optimal OTM.

Like mechanical preparation, silane treatment also has been blamed for procelain fractures at debonding sites by excessively enhancing the bond strength.[33, 36, 46, 50] In Larmour et al.'s study, all samples had silane treatment, without any mecanical preparation. They still found a high incidence of porcelain surface damage visible at debond, particularly in the groups using Transbond XT (TXT) composite resin (3M Unitek, Monrovia, California) where 37.5% of the ceramic samples had visible damage. Thus even without mechanical preparation, one may still obtain porcelain fracture.

From a clinical perspective, it would be prudent to warn patients about the risk of damage to porcelain surfaces prior to the start of treatment and of the possible need to repair or replace them following orthodontic treatment.

2.5 Materials for Custom Base Fabrication

As previously mentioned, adhesion strength can vary significantly not only according to surface preparation but also according to the bonding material used. Clinicians need to be knowledgeable about the various bonding materials so that they can select their materials appropriately. New orthodontic cements, adhesive resins, and hybrid cement-resin combinations offer improved physical properties and clinical benefits, but there are clear differences in their clinical indications and contra-indications.

2.5.1 Cements

Clinical use of GIC for orthodontic use has been reported. They come in two pastes that require mixing. GICs' inhibition of demineralization of adjacent enamel is useful for cementing bands in caries-prone patients. Also, their chemical adhesion and moisture tolerance eliminate the need for etching and drying. As previously stated, studies have shown that brackets cemented with GICs have poorer retention if compared to controls cemented with composite resin.[3, 45] Since GICs offer low fracture resistance, their orthodontic use is mainly limited to band cementation.

Direct bonding method studies have suggested that resin-modified glass ionomer cements (RMGICs) might also provide suitable bond strengths for orthodontic bonding.[33, 51, 52] In addition, it has been shown that brackets cemented with RMGICs will tend to fail at the enamel/cement interface. This may be advantageous for easier cement clean-up at the debonding appointment.[33, 53]

2.5.2 Composite Resins

Composite resins are the most popular choices for bonding brackets. They are either thermo-cured, light-cured, or chemically-activated or dual-activated. Composite resins are a class of materials that do not inherently contain water. To obtain optimal adhesion, composite resins require acid-etched or roughened dry surfaces for best mechanical retention. They are also more fracture resistant than GICs. Unfortunately, composite resins have the disadvantages of not bonding well in the presence of moisture and their attachment to surfaces is primarily mechanical.

Thermo-cured composite resins are available for custom base fabrication. It is dispensed as a single-paste onto the bracket base, which is then placed onto the casts. The resin stays unpolymerized until the cast is cured with heat for at least 15 minutes.[14] Only

thermo-cured and light-cured composite resins allow an unlimited working time before polymerization.[20]

Light-cured composite resins are available and are dispensed as a single-paste. These single-component materials are easier to manipulate. They have little ability to inhibit caries and to remineralize enamel.[3] The composite resin is cured with a handheld curing light or unit. Again, bracket placement can be verified indefinitely before curing, provided that the brackets are not exposed to light.[18] Another possible advantage with light-cured composite resin is the possibility of faster clean-up, as there may be less residual material adherent to the enamel surface after debonding at the end of treatment.[7]

Chemically-activated or auto-polymerizing or dual-activated composite resins are supplied as two-part formulation with a base and catalyst. These materials require hand-mixing on a pad prior to application and start their polymerization as soon as they come in contact with each other, limiting the working time. Handling and applying these materials were problematic, time-consuming, and cumbersome. This step alone can introduce defects such as surface porosity and inevitable inclusions of air bubbles or voids in the bulk material and weak spots. If a dual-activated composite resin is used, a final light-cure is required once the transfer tray is detached from the cast to ensure complete polymerization of the custom bases' centers.[6]

In the end, selection of material required for the fabrication of the custom bases will depend on clinician's preference, clinical bond failure rate and office set-up for staff execution of the multiple laboratory steps.

2.5.2.1 Performance of Thermo-cured Composite Resins

The thermally-cured composite resin Therma Cure (Reliance Orthodontic, Itasca, Illinois) combined with a chemically-cured adhesive resin exhibited lower SBS when compared to other indirect bonding systems *in vitro*.[20] The use of thermo-cured

composite resins have shown several disadvantages including: brackets " drifting " away from their ideal position during their polymerization in a heated toaster oven, confusing and various suggested laboratory protocols, technique sensitivity and time consuming steps. The method is also oven-sensitive according to Moskowitz et al.; an oven thermometer is highly recommended, as temperatures vary between ovens and with the number of casts being cured simultaneously.[6]

2.5.2.2 Performance of Chemically-cured Composites Resins

As previously mentioned, hand-mixing can incorporate air bubbles. Oxygen inside the trapped bubbles theoretically interferes with the complete polymerization reaction and reduces bond strenght.[38] However, it was demontrated that SBS between chemically- and light-cured composite resins were comparable and both were clinically acceptable in an *in vitro* study using the indirect bonding method and tooth substrates.[20]

2.5.2.3 Performance of Light-cured Composites Resins

Studies using extracted bovine and human teeth found that shear bond strengths were comparable when the same light-cure composite resin TXT (3M Unitek, Monroavia, California) was used to bond the brackets directly and indirectly.[20, 54, 55] On a side note, clinicians who use the indirect bonding method still have to be equiped with the materials necessary for direct bonding of accidental bracket failures. They may as well opt for the same light-cured composite resins for both direct and indirect bonding methods for ease of clinic inventory, such as TXT.

2.6 Adhesive Resins for Chairside Step

The adhesive resin materials refered to in this section are used for chairside bracket delivery and are applied to the teeth, the custom composite bases, or both. They are typically light-cured or chemically-cured.

2.6.1 Chemically-cured Adhesive Resins

Chemically-cured adhesive resins are more comfortable for the patient and the clinician, since the transfer trays only need to be seated with finger pressure for about less than 1 minute. No polymerizing device needs to navigate inside the patient's already-crowded mouth. Although active OTM can be initiated earlier, Rossouw et al. found that auto-polymerized materials tend to reach their maximum bond strength after 24 hours.[56]

Common chemically-cured adhesive resin systems require hand mixing. Therefore, to address the disadvantages of two-phase products, "homogeneous polymerization" was introduced with the development of no-mix chemically-cured adhesive resins. Setting of the paste-primer adhesive resins requires intimate contact between the paste and primer, so that diffusion of the components and polymerization can occur.[20] One issue that arises with this formulation lies in a catalyst gradient that is established by means of a diffusion process from the primed tooth surface towards the bracket. Under these conditions, Eliades et al. suspect that bond strength may decrease in the layers where there is less catalyst penetration.[38] Voids or air bubbles can still occur when the no-mix material is placed in contact with each other.

The following is a list of frequently-cited products :

Maximum cure Filled (MC) (Reliance Orthodontic, Itasca, Illinois) is a two-part adhesive resin. It has a filler content of 12%. MC requires mixing in equal parts. It allows 90 seconds of working time from the start of mix. Then a small amount can be applied to the custom bases and the tooth surfaces. Working time can be extend to 3.5 minutes by mixing on a paper covered frozen slab. The manufacturer claims that oxygen does not interfere with polymerization. Time to complete polymerization is not mentioned in the manufacturer's information sheet.

Custom I.Q. (Reliance Orthodontic, Itasca, Illinois) is a similar "fast setting" adhesive resin which comes also in two-parts, A and B. It is a no-mixing adhesive resin that comes with fluoride releasing properties. According to the manufacturer, the transfer tray is held actively in position for 1 minute and then must rest passively for an additional 4 minutes. Part A is applied to the bracket's custom bases and part-B is applied to the tooth substrate.

Sondhi Rapid Set A+B Indirect Bonding Adhesive (SD) (3M Unitek, Mondavia, California) is another so-called "fast setting" no-mix adhesive resin. The tray is held steadily for 30 seconds, then left undisturbed for an additional 2 minutes to allow complete polymerization. The adhesive resin cures as the two components are brought in contact, when the bonding tray is seated in the patient's mouth. It has a filler content of approximately 5% (range 1–10%) (see Appendix 2 : Sondhi Material Safety Data Sheet). The universal adhesive resin B is applied with a microbrush to the bracket's custom base and the unfilled catalyst A is painted on the tooth surface.

Figure 13: Sondhi Rapid Set A+B Indirect Bonding System (3M Unitek, Mondavia, California). (Image adapted from www.multimedia.3m.com)

2.6.1.1 Performance of Chemically-cured Adhesive Resins

In Miles and Weyant's clinical split-mouth *in vivo* study, the authors compared and evaluated the clinical performance of two chemically-cured adhesive resins using the indirect bonding technique: SD and MC filled adhesive resins. Over a six-month period, a total of 726 brackets were bonded on 40 consecutive patients in the author's private practice. SD had a 9.9% failure rate, while MC had a 1.4% failure rate (P=0.0001). When comparing the two chemically-cured adhesive resins for each arch, it was only in the mandibular arch that SD had a statistically significant higher number of breakages than MC (P = 0.001). It has been suggested that a source of weakness when using indirect bonding with unfilled adhesive resins is the presence of marginal voids. To fill these voids, Miles and Weyant painted each bracket's composite custom base with methyl methacrylate monomer Orthocryl (Dentaurum, Ispringen, Baden-Württemberg) 10 minutes prior to bonding to enhance adhesion.[57] Both MC and SD are partly filled adhesive resins, which are more viscous, making it less likely for voids to occur than with unfilled adhesive resins. In addition, MC has almost twice the filler content than SD ; this may have an impact on the observed difference between the two adhesives resins. In conclusion, the author stated that both chemically-cured adhesive resins, SD and MC, were clinically suitable for the indirect bonding of orthodontic brackets.

2.6.2 Light-cured Adhesive Resins

With light-cured adhesive resins, the polymerization does not start until it is exposed to a visible light source. These materials allow optimal adaptation and penetration of the adhesive resin to the etched enamel as the tray is carefully seated in mouth, theoretically permitting higher bond strengths and lowering failure rates. Some argue that light-cured adhesive resins have an additional advantage by reducing clinical time : once exposured to visible light source, the material is completely polymerized, and transfer trays can then be removed immediately.[7] The clinician must select a transfer tray material that

allows light penetration into the adhesive resin. McCrostie et al. recommend vacuum-formed transfer trays or Memosil CD (Heraeus Kulzer, Hanau, Postfach) trays because they tend to be superior and less complicated to use in his hands.[58]

Unfortunately, light-cured adhesive resin bonding is a more technique sensitive for the chairside delivery of brackets. Clinicians must hold the transfer tray in place, with a constant finger pressure on the teeth, without disturbing the tray for the duration of the polymerization of each tooth within the arch with a hand-held unit. Therefore, it is combersome for both the clinician and the patient since the tray, fingers, and curing unit are simultaneously inside the patient's mouth.

As there is less interest in this polymerization approach, there are fewer products of this family on the market designed specifically for indirect bonding. Most authors have published *in vitro* studies using the light-cured adhesive resin Orthosolo (Ormco Corporation, Glendora, California).[55] Orthosolo is commonly used for direct bonding methods. In the indirect bonding method, Enlight LV dual-cure composite resin (Ormco Corporation, Glendora, California) is used both as the custom base fabrication and during chairside bracket delivery as an adhesive resin system, in combination with OrthoSolo applied to the tooth. Once the transfer tray with the custom bases is seated in mouth, light-curing for 10 seconds gingivally is followed by another 10 seconds occlusally for every single tooth chairside. Tray removal can be done immediately or after complete polymerization of the dual-cure Enlight LV.[58]

2.6.2.1 Performance of Light-cured Adhesive Resins

Linn et al.'s indirect bonding study on extracted human teeth found that light-cured adhesive resins performed as well as the chemically-cured SD for both direct bonding and indirect bonding.[55] However, results from Daub et al.'s indirect bonding study suggest that light-cured adhesive may be more susceptible to the thermal stress of thermocycling

than the chemically-cured adhesive resins. The survival rate dropped by 10% following thermocycling.[54]

Read et al.'s *in vivo* clinical trial carried over a 30 month period investigated the failure rate of indirectly bonded brackets in which an unspecified light-cured unfilled adhesive resin and Opalux (I.C.I. Dental, Macclesfield, U.K.) composite custom bases were used. The author found an adequate clinical performance with a low failure rate of 6.5%, comparable to other well-documented clinical trials on indirect bonding. No statistically significant difference was detected between the anterior and posterior failure rates when the data for both arches were analyzed either separately or in combination ($p<0.01$).[7] This *in vivo* study shows that even unfilled adhesive resins perform clinically.

2.7 Measuring Shear Bond Strength

Values for SBS can only be tested and mesured in a laboratory setting or *in vitro* environments. Bond force is usually measured in shear or tension on a universal testing machine, although torsional testing has been reported.[56] In shear testing, the brackets are loaded by a blade in compression or by a wire in tension, so that the brackets slide parallel off the substrate. Unfortunately, pure shear loading is difficult to achieve. Most shear testing includes components of peeling, tension, and torsion as well. Both shear and tensile loading modes are valid tests for studying orthodontic bonding.[2] However, many investigators believe that testing in tension or torsion loading modes are less relevant for clinical applications, and have thus placed focus on shear testing for ease of reproductibility of protocols.[59]

The average force transmitted to a bracket during mastication has been reported to be between 40-120 Newtons (N). Bond strength is calculated by dividing the applied force by the surface area of the bracket base, 1 MPa = 1 Newton/mm^2 .[56] In 1975, Reynolds stated that shear bond strengths in the range of 5.88 to 7.85 MPa were required for brackets

bonded to teeth to overcome intraoral and orthodontic forces.[60] These reference numbers have since been frequently used in multiple SBS testing studies. A study by Bishara et al. suggested that the mean safe debonding strength should be less than 11.28 MPa.[61] Rossouw et al. later on suggested that the optimum SBS range is between 5.88 and 13.53 MPa, where the higher value represents the SBS where enamel fractures can appear based on Thurmond et al.'s findings.[56, 62]

2.7.1 Factors Affecting Bond Strength

Many variables must be taken into account when interpreting data and results of bond test studies. These include:

1. Type of surface (teeth vs porcelain)
2. Type of porcelain (leucite vs feldspathic vs alumina)
3. Type of bracket base (mesh size and topography)
4. Type of surface treatment (mechanical vs chemical preparation, and its various products and concentrations)
5. Type of bonding method (direct or indirect)
6. Type of composite resin for custom bracket base (chemically-, thermally- or light-cured material and its various products available on the market)
7. Type of adhesive resin for chairside delivery in the case of indirect bonding method (chemically-, thermally- or light-cured material and its various products available)
8. Type of aging process (water storage, thermocycling, etc).

An *in vitro* study looked at the factors previously enumerated and their effect on the SBS of directly bonded metal brackets using TXT on porcelain. The authors found that surface treatment was the only factor that significantly affected the SBS in this direct bonding experiment on porcelain crowns ($p<0.001$), shown in Figure 14. SBS was significantly different between the following these three porcelain surface treatements:

sandblasted + HFA, sandblasted + PA and sandblasted only ($p<0.001$). Other variables that were examined included the material of the bracket (metal or ceramic), and the type of ceramic used (IPS Empress or In-Ceram).[27]

Table 2 *F* and *P* values for the effect of the studied variables on shear bond strength.

Variable	*F* values	*P* values
Type of bracket	1.547	0.217
Type of porcelain	1.203	0.276
Surface treatment	11.137	***
Type of bracket × type of porcelain	0.219	0.641
Type of porcelain × surface treatment	0.947	0.392

***$P < 0.001$.

Figure 14: Studied variables that can affect SBS.
Only the surface treatment significantly increased or decreased SBS.
(Image adapted from Abu Alhajia et al.[27])

Interestingly, Eliades et al. have repeatedly found that bond strength values largely depended on bracket base's mesh design and surface, regardless of the nature of the restorative substrate or their topographic characteristics.[38, 59]

2.7.2 Enamel : Shear Bond Strength Comparisons

Initially, clinical bond failure rates for indirect bonding were higher when compared with rates for direct bonding, 13.9% and 2.5% respectively.[10] However, with modifications and improvements to the indirect technique, the two systems now have similar bond strengths and failure rates. In fact, many authors have found no statistically significant difference in SBS between direct and indirect, *in vivo* and *in vitro* studies, when tested on natural teeth.[7, 15, 16, 54, 57, 63, 64] Table 3 contains a summary of the following *in vitro* studies' experimental groups, results and conclusions.

Linn et al.'s study used 60 extracted human premolars. They found no significant difference in SBS between direct and indirect bonding groups.[55] Daub et al.'s study replicated Linn et al.'s study with an additional experimental step of thermocycling. No significant difference in SBS was found.[54] Yi et al. also found no statistically significant difference between their 2 test groups.[15] Klocke et al.'s results demonstrated significant differences in SBS ($p<0.05$). Both groups which used thermally-cured composite resin and indirect bonding had significantly lower SBS, of 7.28 ± 4.9 and 7.07 ± 4.1 MPa, when compared with their direct bonded light-cured composite resin control group.[20] All these four studies' surface treatment protocols did nonetheless provide mean SBS that were either in the optimum range suggested by Rossouw et al., of 5.88-13.53 MPa, or a little higher.[56]

Shiau et al.'s study was slightly different. Custom bases were aged for seven days in a dry environment, prior to chairside delivery. This is clinically a more realistic situation, as bases are frequently fabricated a few days before the patient's scheduled bonding appointment. Yet the author found no evidence to suggest that an aged composite would predispose the enamel-bracket system to fail at the more at the adhesive resin-composite resin interface. They also did not find any statistically significant difference in the SBS between direct and indirect methods, and all groups provided adequate bond strength for OTM.[65].

Table 3: SBS comparisons between direct and indirect bonding with teeth.

Paper	Bonding Method	Surface Teeth	Groups	Mean SBS (MPa)	Conclusion SBS	Conclusion ARI
Linn[55]	Direct and Indirect	60 extracted human teeth	1. (D) TXT + TXT adhesive = control group 2. (I) TXT + SD 3. (I) E-LV + Orthosolo	16.27 ± 4.74 13.83 ± 4.27 14.76 ± 4.06	No statistically significant difference	No statistically significant difference
Daub [54]	Direct and Indirect + thermocycle	60 extracted human teeth	1. (D) TXT + TXT adhesive = control group 2. (I) TXT + SD 3. (I) E-LV + Orthosolo	13.6 ± 2.9 12.3 ± 3.0 11.6 ± 3.2	No statistically significant difference	Group (TXT +SD) had higher bond failure
Yi [15]	Direct and Indirect + thermocycle	54 extracted human teeth	1. (I) APC + SD 2. (D) APC + TXT adhesive = control group	11.2 ± 2.6 10.9 ± 2.9	No statistically significant difference	No statistically significant difference
Klocke [20]	Direct and Indirect	100 extracted bovine teeth	1. (I) TC + MC 2. (I) TC + Custom I.Q. 3. (I) TXT + SD 4. (I) Phase II + MC 5. (D) TXT = control group	7.28* ± 4.88 7.07* ± 4.11 14.99 ± 2.85 15.41 ± 3.21 13.88 ± 2.33	Groups with thermally-cured composites (TC + MC) and (TC + Custom IQ) had significantly lower SBS when compared to other groups	Groups with thermally-cured composites had significantly higher bond failure rates
Shiau [65]	Direct and indirect. 7-day aging for custom bases with indirect method only	60 extracted bovine teeth	1. (D) metal brackets + Concise = control group 2. (I) metal brackets + Concise + Concise 3. (D) ceramic brackets + Concise = control group 4. (I) ceramic brackets + Concise + Concise	11.7 ± 2.2 11.8 ± 2.0 8.3 ± 3.0 8.6 ± 2.8	No statistically significant difference	No statistically significant difference

D: Direct bonding technique, I: Indirect bonding technique, TXT: Transbond XT (light-cure composite resin), SD: Sondhi Rapid-Set A+B (no-mix chemically-cured adhesive resin), E-LV: Enlight-LV (dual-cured composite resin), APC: APC pre-applied composite bracket system (light-cured composite resin), TC: Therma Cure (thermally-cured composite resin), MC : Maximum Cure (chemically-cured adhsive resin), Concise (two-paste chemically-cured composite resin)

** :statistically significant $p<0.05$*

2.7.3 Porcelain : Shear Bond Strength Comparisons

Bonding to ceramic is preferentially done through glass particles. Therefore bonding to traditional feldspathic ceramic is a predictable procedure with reliable results. However, the composition and the physical properties of leucite-reinforced or lithium-disilicate ceramics are different and may require alternative bonding protocols.[32] Calamia found that the bond strength of composite resin to aluminous porcelain, due to its homogeneous surfaces, was inferior to that of feldspathic porcelains.[66] On the other hand, more heterogeneous surfaces will have inherently larger flaws and be more susceptible to fracture and weaker bond strengths according to Mair et al.'s findings.[29]

The following studies on porcelain surface treatments and SBS were conducted according to the direct bonding method (Table 4). One can grasp the complexity of bonding to ceramic surfaces by noticing the numerous different conclusions.

Karan et al. studied 70 samples each of three different types of ceramic materials: feldsphatic porcelain, leucite-based ceramic, and lithia disilicate-based ceramic.[32] After direct bonding with TXT composite, all samples underwent 24 hours storage and 500 cycles of thermocycling. The authors concluded that all surface treatments, except for sandblasting only, yields theoretically acceptable bond strength for OTM with metal brackets, regardless of the type of porcelain. In the event that the ceramic type was not known, the author recommended silane combined with silica coating or HFA after sandblasting for porcelain surface treatment when bonding orthodontic brackets.

In Larmour et al.'s study, 80 porcelain discs were divided into four groups, in which all were treated with silane after acid etching with either PA or HFA. No mechanical treatments were performed. The two composite resin groups Transbond (3M Unitek, Monrovia, California) had the highest mean bond strength values at 7.9 and 9.7 MPa. However, the two RMGICs groups with Fuji Ortho L.C. (G.A.C. Corporation, Tokyo,

Japan) had the lowest mean bond strength values at 6.3 and 1.8 MPa. Only the group treated with PA and RMGIC had significantly lower SBS values than the other groups ($p<0.0001$).[33]

Turk et al.'s study was on feldspathic and IPS Empress 2 ceramics and varying surface treatments. However, it was only in one group that a statistically significant lower SBS was observed ($p<0.05$) : HFA treatment followed by silane application on feldspathic porcelain. One would actually least expect such result since feldspathic porcelain has a greater content of glass than IPS Empress 2, which is a lithium-disilicate ceramic. All other groups had similar SBS.[67]

Abu Alhaija et al.'s *in vitro* study was conducted on 96 porcelain crowns fabricated to resemble premolars. They were either IPS Empress 2 or In-Ceram all-ceramic crowns. Metal and porcelain brackets were tested as well. The highest mean for SBS of 120.15 ± 45.05 N was obtained in the ceramic brackets bonded to sandblasted and 9.6% HFA treated IPS Empress 2 group. The lowest mean SBS of 57.86 ± 26.20 N was in the metal brackets bonded to sanblasted only In-Ceram group. In this study, acid etch application to sandblasted surfaces significantly increased the SBS ; the authors concluded that the surface treatment was the only factor that significantly influenced SBS ($p<0.0001$), and that porcelain type or bracket material had no effect.[27]

These same authors had previously concluded in another experiment that, even if the ceramic composition were different, all three tested groups provided adequate clinical bond strength for OTM. However, their IPS Empress group did have significantly lower SBS ($p<0.001$) than the other tested groups of In Ceram and conventional porcelains.[68]

To date, no study has been published on the topic of shear bond strength of indirect bonding methods and materials to porcelain surfaces. Comparison between direct and indirect bonding methods to porcelain is impossible for the time being.

Table 4: Summary of SBS studies with various porcelain surface treatments.

Paper	Bonding Method	Surface Porcelain	Groups	Mean SBS	Conclusion SBS	Conclusion ARI
Larmour [33]	Direct: Composite (Transbond) versus RMGICs (Fuji Ortho L.C.)	80 porcelain denture teeth (Ivoclar-Vivadent) : Divided into 4 equal groups. No mechanical preparation	Composite resin : 1. PA + S 2. HFA + S RMGIC : 3. HFA + S 4. PA + S	(Mpa) 83.4 ± 45.2 103.2 ± 45.8 66.3 ± 37.0 18.7* ± 6.9	All groups had adequate SBS. Group (PA + Fuji Ortho L.C.+ S) had significantly lower SBSs when compared to other groups	Groups with (Fuji Ortho L.C) had no visible porcelain damage. Fuji had significantly lower ARI scores than the composite group. The composite group had highest percentage of damaged porcelain 40% and 35%.
Karan [32]	Direct (TXT system of composite and adhesive) + thermocycle	210 discs : Divided in 3 equal groups, then into 5 equal sub-groups	Feldspathic : - Al_2O_3 30 um - Al_2O_3 30 um + HFA - Al_2O_3 30 um + HFA + S - Al_2O_3 30 um + S - Al_2O_3 30 um + S IPS Empress: - Al_2O_3 30 um - Al_2O_3 30 um + HFA - Al_2O_3 30 um + HFA + S - Al_2O_3 30 um + S - SC + S IPS Empress 2 - Al_2O_3 30 um - Al_2O_3 30 um + HFA - Al_2O_3 30 um + HFA + S - Al_2O_3 30 um + S - SC + S	(Mpa) 3.2* ± 2.7 11.3 ± 4.1 10.5 ± 6.0 10.7 ± 5.1 15.2 ± 5.9 3.9* ± 3.0 14.7 ± 5.8 9.9 ± 5.0 12.3 ± 8.5 13.4 ± 6.5 3.1* ± 2.6 8.6 ± 4.8 5.7 ± 3.6 11.8 ± 6.1 13.2 ± 7.7	All sub-groups (Al_2O_3 30 um) had significantly lower SBSs when compared to other groups, and did not provide adequate SBS for OTM. Silane did not increase SBS	Sub-Groups (SC + S) and (SB + S) had the highest incidence of cohesive fractures : - leucite had more incidence of porcelain fractures than other types of porcelain. - fractures seem to occure more when silane was applied
Abu Alhaija [27]	Direct (TXT system of composite and adhesive)	96 crowns: IPS-Empress 2 Or In-Ceram ingots	Metal brackets : 1. HFA + IPS Empress 2 2. HFA + In-Ceram Ceramic brackets : 3. HFA + IPS Empress 2 4. HFA + In-Ceram Metal brackets : 5. PA + IPS Empress 2 6. PA + In-Ceram 7. Al_2O_3 50 um + IPS Empress 2 8. Al_2O_3 30 um + In-Ceram	(Newtons) 101.7 ± 52.9 106.8 ± 34.8 120.2 ± 45.1 115.2 ± 32.6 110.3 ± 37.0 87.0 ± 37.1 59.7* ± 27.3 57.9* ± 26.2	All groups had adequate SBS. Groups without acid etching (SB+ IPS Empress 2) and (SB +In-Ceram) had significantly lower SBSs when compared to other groups.	The greatest incidence of ceramic fracture was with groups treated with (HFA).

Paper	Bonding Method	Surface Porcelain	Groups	Mean SBS	Conclusion SBS	Conclusion ARI
Türk [67]	Direct (TXT system of composite and adhesive) + Thermocycle	120 discs : 2 groups of 60 samples each,	Glazed feldspathic : 1. Al_2O_3 25 um + S 2. Al_2O_3 50 um + S 3. HFA + S 4. extra fine bur + S 5. fine bur + S IPS Empress 2 1. Al_2O_3 25 um + S 2. Al_2O_3 50 um + S 3. HFA + S 4. extra fine bur + S 5. fine bur + S	(MPa) 17.9 ± 3.2 14.7 ± 3.2 5.4* ± 2.6 26.0 ± 5.7 26.4 ± 5.0 22.6 ± 2.5 26.2 ± 3.7 11.1 ± 4.1 24.3 ± 4.9 28.2 ± 3.6	Significant differences SBS and surface conditioning. Lowest SBS was in group (HFA+Silane), which is less than optimal.	All samples failed at the ceramic interface. (adhesive failure). No ceramic fractures noted.
Abu Alhaija [68]	Direct (TXT system of composite and adhesive)	60 crowns : 3 groups of 20 crowns all treated the same way	1. In-Ceram : Al_2O_3 50 um + HFA + S 2. IPS Impress : Al_2O_3 50 um + HFA + S 3. Conventional : Al_2O_3 50 um + HFA + S	(Newtons) 78.9 ± 13.5 67.4* ± 9.0 80.5 ± 13.4	All groups had adequate SBS. IPS Impress group had significantly lower SBS than the other 2 types of ceramics	(Barely discussed)

*PA: phosphoric acid, HFA: Hydrofluoric acid, Al_2O_3 : alumium oxide sandblasting, APF : acidulated phophate fluoride, S: Silane, SC: Triboche/mical silica coating, BA : bonding agent, * :statistically significant $p<0.05$*

2.8 Adhesive Remnant Index

2.8.1 Background and Relevance

The site of bond failures can be quantified with the Adhesive Remnant Index (ARI). The index scores the amount of resin remaining on the tooth after bracket debonding. All orthodontic bonding systems involve at least three interfaces: tooth interface, resin interface, and the bracket interface. As previously mentioned, cohesive failures can occur within any of these components. Adhesive failures occur between the tooth-resin system or bracket- resin system. An observation is that authors do not differentiate between the residual adhesive resin and residual composite resin that remains on the tooth when they score; it is all combined under ARI. [2] Powers further highlighted that isolating the weak

link is complicated if bond failure occurs in two of the three interfaces, which happens frequently.[2]

Many studies have used the ARI scores developed originally by Årtun and Bergland to assess the amount of resin remaining on the tooth surface after orthodontic bracket debonding.[2, 42, 69] The original ARI scores were defined from 0 to 3. The ARI was then modified by Bishara et al., who gave the scores from 0 to 4 to include a score representing porcelain fractures.[70] Unfortunately, many studies use other variations of the ARI index. Due to a lack of methodology standards and variability in the ARI index scores, the reader must be careful when interpreting ARI numeric scores and results.

In an orthodontic clinical environment, obtaining ARI scores representing a small amount of residual adhesive resin on the tooth substrate is prefered, since it implies less resin clean-up and faster polishing. Initially, Hocevar et al. reported that 72% of the brackets bonded with the « Original Thomas Technique » failed at the enamel-resin interface, which was desirable for clean up.[64] Nowadays, the general failure site has been identified at the bracket-resin interface, meaning more resin clean-up but an increased longevity of the tooth substance.[20] As mentioned previously, it is suggested to stay in the "optimum" range of 5.88 and 13.53 MPa, above which a higher risk of enamel or cohesive fractures may occur.[56, 62]

Although a reduced clean-up time after debond is beneficial, it more desirable to concentrate on avoiding a cohesive fracture or damage of the porcelain. This study will focus on the presence or absence of porcelain fractures after debonding and investigating ways to reduce their occurrence.

2.8.2 Reports of Porcelain Fractures

In vitro studies found no enamel fractures when tested with direct and indirect bonding methods (Table 3). Groups that used TXT + SD found no correlation between SBS and ARI scores. Thermocycling did not alter the fracture site.[54, 55]

Unfortunately, porcelain fracture after debonding procedures is a common complication in direct bonding studies (Table 4). Certain types of ceramics, such as leucite-reinforced porcelain, were more susceptible to debonding fractures, as shown in Karan et al.'s study where 18% of them were damaged.[32] Most of Larmour et al.'s study groups, all samples had silane application. The porcelain-resin interface was the most common site of failure for all groups. The groups bonded with RMGIC experienced no porcelain damage, while groups bonded with composite resin had high percentages of damaged porcelain surfaces at 40% and 35%, respectively.[33] Along with certain types of ceramics, certain types of resin systems can increase the occurrence of fractures.

Some fractures were more frequent depending on the surface treatment. A 2010 study found no statistically significant difference in ceramic fractures between the IPS Empress 2 and In-Ceram groups. They noted greatest cohesive fracture incidence when the surfaces were treated with 9.6% HFA.[27] In other *in vitro* studies by Turk et al. and Heravi et al., no fracture in the ceramic body was observed even with the application of HFA.[42, 67] More contradictory evidence from Bourke et al.'s study states that the amount of composite resin remaining on the porcelain surfaces was independent of the bonding regimen employed in their *in vitro* study.[34] Therefore no particular surface preparation protocol can predictably yield more or less composite resin residue on the tooth substrates after bracket removal.

2.9 Thermocycling

Orthodontic composite and adhesive resin are routinely exposed to temperature variations in the oral cavity. Intra-oral temperatures vary between 0º C when eating ice cream to 60º C when eating a hot cheese sandwich.[29] Thermocycling, usually between 5°C and 55°C water baths, thus simulates the temperature dynamics of the oral environment and recreates the aging process. Bishara et al. suggested that thermocycling be part of the testing protocol of new resins.[71]

Studies that incorporated thermocycling demonstrated statistially significant reductions in SBS between orthodontic resins and tooth or porcelain surfaces, in both direct and indirect bonding studies. Klockowski et al. observed a significant decrease in SBS ($p<0.01$) between metal brackets bonded to teeth using four different bonding agents. Three were GICs and the fourth was an auto-polymerizing adhesive resin; the auto-polymerizing adhesive resin showed the greatest decrease.[72] Arici et al. found a significant reductions ($p<0.001$) of 11.1% and 26.5% in SBS after 200 and 20,000 thermocycles respectively, after bonding brackets with RMGICs on teeth. Similarly, he found a 5.7% and 17.9% reduction of SBS when using adhesive resins.[73] Daub et al. found statistically significant reductions in SBS for both direct and indirect bonding groups ($p<0.001$) of 16.7%, 11.1%, and 15.4% in all three groups of teeth after 500 thermocycles.[54] Bourke et al. conducted a similar study and found that thermocycling caused a significant reduction in SBS to porcelain substrates ($p<0.001$).[34] Hence thermocycling is highly recommended for SBS test protocols.

Although the International Organization for Standardization (ISO) has provided thermocycling criterias for bonding studies, there has been a lack of consistency in experimental protocols, typically varying from 500-5000 cycles. Five hundred cycles is the accepted ISO standard for adhesion testing.[32]

Authors have tried to explain how thermocycling decreases the adhesion forces. It has been suggested that the reduction in bond strength in thermocycled specimens could be due to differences in the coefficient of thermal expansion of the adhesive or composite resin, the metal bracket, and enamel or porcelain. The cycles at two different extreme temperatures could also cause any weakened areas within the bond layers to grow progressively in size.[32]

Another possibility for the decrease in bond strength after thermocycling could be attributed to the increased water absorption/contamination or solubility of the composite, or both. Many dental materials are known to interact with components of the oral environment. In cases of composite resin, the principal interaction occurs with water, which diffuses into the matrix causing hygroscopic expansion of the material as well as a chemical degradation of the material. SBS studies have shown a decrease in bond strength of orthodontic composites after immersion in water. The greatest loss of bond strength occurs initially, but there is a also time-dependent loss in bond strength and resin degradation observed by Meng et al. and Yap et al.[54, 74, 75] In addition, an increase in sensitivity of the dental materials to the combined effect of water absorption and temperature variation can ultimately alter their bond strength.

3. EXPERIMENTAL HYPOTHESES

FIRST HYPOTHESIS :

Different chemical surface treatments of the porcelain will yield significantly different shear bond strength (SBS).

SECOND HYPOTHESIS :

Mechanical treatment of porcelain surfaces will enhance shear bond strength of metal brackets to porcelain.

THIRD HYPOTHESIS:

No difference is suspected in the type of fracture observed between the chemically- and mechanically-treated porcelain surfaces.

4. SCIENTIFIC ARTICLE

In preparation for submission to the AJODO.

ABSTRACT

Background : Bond strength at the metal-ceramic interface of auto-polymerizing resins used in orthodontic indirect bonding has not yet been evaluated and a literature-based clinical protocol is lacking.

Goals : 1) To compare shear bond strength (SBS) between metal brackets and differently treated porcelain surfaces; 2) suggest efficient and predictable chairside approaches.

Materials and methods : Ninety leucite discs (6 groups; n=15/group) were prepared following 6 combinations of mechanical (+/- bur roughening) and chemical (hydrofluoric acid, primer, silane) treatments. Metal brackets with custom composite resin bases Transbond XT (3M Unitek, Monrovia, California) were bonded with the adhesive resin system Sondhi A+B Rapid Set (3M Unitek, Monrovia, California). Samples were stored (H_2O/24hrs), thermocycled (500 cycles) and tested (Instron, Norwood, Massachusetts). Maximum SBS and adhesive remnant index (ARI) scores were collected for each sample. ANOVAs were performed on ranks since data was not normally distributed, and then adjusted with post-hoc Tukey. A Kruskall-Wallis, a Mann Whitney U pairwise comparison and a Weibull analysis were also performed.

Results : SBS medians of groups ranged from 17 MPa (- bur + hydrofluoric acid) to 27MPa (- bur + hydrofluoric acid + silane). Bur roughening did not affect bond strength. The chemical preparation of (- bur + primer + silane) showed significantly higher SBS than (- bur + hydrofluoric acid) preparation ($p<0.05$) while having similar SBS to the popular recommended protocol (- bur + hydrofluoric acid + silane). ARI scores were significantly lower ($p<0.05$) in group (- bur + hydrofluoric acid), while all other 5 groups were not different from each other. Percentage of porcelain damage in these 5 groups were very high at 80-100%.

Conclusion : All the tested surface preparations combinations provided clinically adequate adhesion for orthodontic tooth movement. Silane and primer combination for porcelain surface preparation is clinically attractive as it is safe and simple and provides great adhesion for orthodontic tooth movement. It is wise to warn patients that there is a risk of porcelain fractures when debonding brackets.

Keywords: Porcelain, Ceramic, Surface preparation, Indirect bonding, Sondhi, Metal bracket, Orthodontic

BACKGROUND

The increased demand among adults for orthodontic treatment generally leads to more frequent bonding of orthodontic attachments to various non-enamel surfaces.[76] Ceramics or porcelain are commonly used as the esthetic option for crowns and veneers. Unfortunately, the bond strength of composite resins to ceramic restorations may be insufficient as porcelain does not bond readily to other materials. Combinations of various mechanical and chemical conditioning methods have been suggested to alter the surface characteristics of porcelain to facilitate bonding.[27, 68, 73]

Mechanically preparing the porcelain is commonly achieved with coarse or fine diamond burs, green stones, abrasive disks or sandblasting with aluminium oxide in order to remove the porcelain's glaze.[32-35] Chemical preparations of the porcelain can be accomplished through etching, either with 1.23% acidulated phosphate fluoride, 9.6% hydrofluoric acid or 37.5% phosphoric acid; or through coupling agents.[32, 33, 36] The application of hydrofluoric acid requires vigilance as it is toxic and can burn soft tissues. Silane is a coupling agent, but its ability to increase bond strength is questionable when bonding with composite resins; it was occasionally reported to have no effect while adding an additional chairside step.[32, 48]

Bracket bonding methods have also evolved with time. The direct bonding technique of orthodontic brackets onto patients' teeth is the most popular method of delivering brackets. The technique's drawbacks include difficult access, visualization, isolation, and muscle soreness for the patient and the operator. The indirect bonding technique was developed to counter these problems.[6-8, 11] Many adhesive resin systems originally designed for the direct bonding method turned out to be disappointing when used indirectly. The first versions of adhesive resins developed specifically for the indirect bonding method had higher clinical bond failure rates than the direct bonding resins, 13.9% versus 2.5% respectively.[10] Today, after research and development of the technique, the

two bonding methods now have similar bond strengths and failure rates.[7, 15-17, 54, 55, 57, 63, 64]

Studies on orthodontic brackets bonded directly to ceramic surfaces have shown that most combinations of at least two surface treatements provided acceptable clinical strength for orthodontic tooth movement (OTM).[27, 32-34, 42, 68] However, indirect bonding of brackets to ceramic surfaces has not yet been evaluated. Without a defined literature-based clinical protocol, the following undesirable consequences can occur:

1. Poor chair-time management
2. Increasing frequency in emergency bracket loss
3. Increased treatment time/additional patient visits
4. Porcelain fracture when debonding brackets
5. Additional cost in materials and personnel

The primary goal of the study is to compare the shear bond strength (SBS) of various porcelain surface preparations and materials destined for the indirect bonding method. Secondary goals involve the determination of a porcelain surface preparation protocol which can reduce the risk of irreversibly damaging the porcelain after debond. Ideally, a clear clinical protocol that yields predictable results for fixed orthodontic appliance treatment from start to finish is desirable; one that balances sufficient bond strength for OTM, while minimizing or eliminating porcelain fracture when brackets fail or debond.

It is first hypothesized that different chemical surface treatments of the porcelain will yield significantly different SBS. It is secondly hypothesized that mechanically treating porcelain surfaces will also enhance SBS of metal brackets to porcelain. Finally, the third hypothesis is that no difference is suspected in the type of fracture observed between the chemically- and mechanically-treated porcelain surfaces.

MATERIAL & METHODS

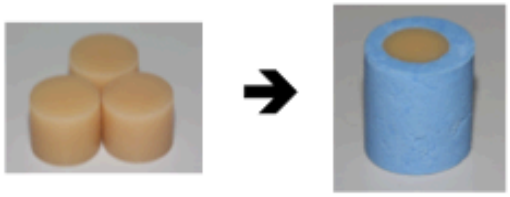
SAMPLE PREPARATION :

Ninety leucite-reinforced porcelain discs by Finesse All-Ceramic (Dentsply GAC, Bohemia, New York) measuring 8 mm in height and 10 mm in diameter were cleaned with alcohol, rinsed and dried. These discs are industrially milled and glazed by Dentsply GAC. All discs were examined to ensure surface perfection and absence of irregularities.

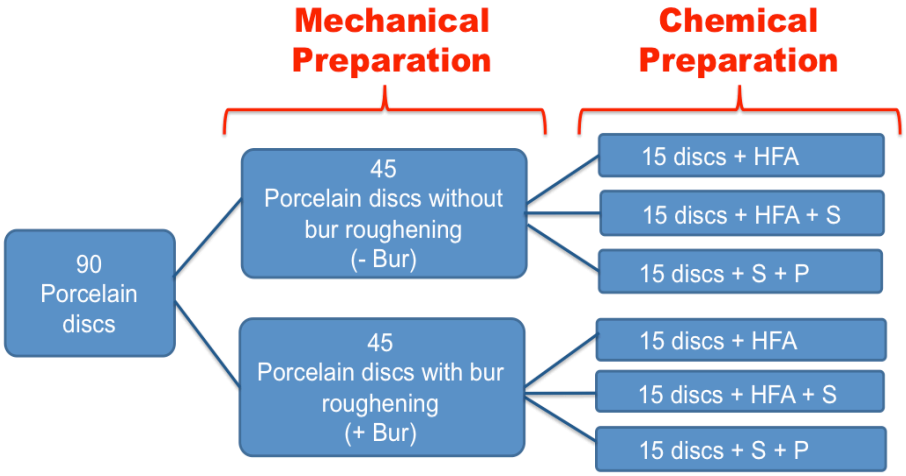
Individual discs were mounted in individual cold acrylic cylinders of Instant Tray Mix (Lang Dental MFG Co., Wheeling, Ilinois) to facilitate shear testing (Figure 1). To fabricate consistently identical acrylic cylinders, a series of plastic tubes measuring 15 mm in diameter and 20 mm in height were used as molds. The inside surface of the tubes were covered with a separator (Vaseline Petrolium-Jelly, Unilever) to facilitate removal of the cylinders after polymerization. The acrylic's liquid monomer and powder were mixed according to the manufacturer's recommendations and compacted into the plastic molds. The porcelain discs were inserted into the center before complete acrylic polymerization. A flat surface (a glass mixing slab) was used to ensure that the porcelain disc was flush with the mold. Excess flash of acrylic at the edge of the mold was removed before cold curing was complete. Once cured, the cylinders were removed by pushing them through the molds at either ends. The 90 samples were then divided into six groups of 15 discs/group, for a total of six surface preparation combinations of mechanical treatments (with or without fine diamond bur roughening) and chemical treatments (hydrofluoric acid, silane, primer).

The six groups of surface treatments combinations were as follows: hydrofluoric acid etching only (- Bur + HFA), hydrofluoric acid etching followed by siliane application (- Bur + HFA + S), silane application followed by primer application (- Bur + S + P), fine diamond bur roughening and hydrofluoric acid etching (+ Bur + HFA), fine diamond bur roughening followed by hydrofluoric acid etching and then silane application (+ Bur +

HFA + S), fine diamond bur roughening followed by silane application as well as a primer (+ Bur + S + P). All six groups are displayed in a schematic representation in Figure 2.



Article Figure 1: Finesse All-Ceramic discs or ingots mounted in blue acrylic cylinders. (Images courtesy of Dr. Stephanie H. Mai, Université de Montréal)



Article Figure 2: Pocelain surface preparations.
HFA: Hydrofluoric Acid 4% Porc-Etch (Reliance Orthodontic, Itasca, Illinois),
S: Porcelain Conditionner/ Silane 1-10% (Reliance Orthodontic, Itasca, Illinois),
P: Primer Assure (Reliance Orthodontic, Itasca, Illinois)

Laboratory step: Custom base fabrication

In a clinical setting, alginate impressions of the patient's teeth are used to make models replicating the clinical situation. Ideal placement of brackets is critical for

individual tooth anatomy and patient treatment goals. However, since the porcelain discs are industrially milled and flat, alginate impressions of all 90 samples of the flat acrylic cylinders was not required. Green stone was mixed under vacuum then poured onto a glass surface to create a flat stone model that mimicked the smooth flat surface of the porcelain discs. The stone was allowed to dry overnight. Two thin coats of Al-Coat (L.D. Caulk Company, Denstply, Bohemia, New York) were applied to the green stone model and allowed to dry for 10 minutes. Stainless steel brackets for tooth #41 SPEED (Strite Industries, Cambridge, Ontario) were chosen for their relatively flat bracket base. Custom composite bases were made with light-cured Transbond XT (TXT) composite resin (3M Unitek, Monrovia, California). The composite resin was applied to the bracket bases. The brackets were then positioned onto the flat stone model by applying 250 grams twice to recreate consistent custom base resin thickness between the model and the bracket. A tension gauge (CORREX, Koneiz, Switzerland) was used to measure the force. Once all 90 SPEED brackets were positioned on the stone model, the custom composite bases were cured in a TRIAD 2000 light curing unit (Dentsply, Bohemia, New York) for 10 minutes, twice, for a total of 20 minutes.

Following bracket bonding to the model, the next step in a clinical situation is the fabrication of transfer trays for each arch to preserve the ideal bracket positions. The trays allow the transfer of the brackets, with their custom made composite bases for each tooth's anatomy, into the patient's mouth. This step was deliberately omited in this study because the preservation and transfer of ideal bracket positions from the model to the discs was not necessary. The next steps are as per clinical protocol. Custom bases were removed from the stone model after letting the model soak in a tap water bath for 45 minutes. After drying the brackets with an air gun, all brackets were repolymerized in the TRIAD unit for 10 minutes. The custom composite bases were then individually micro-etched with 3 shots of 50 μm aluminium oxide particles, for 1 second each shot, at a distance of 1-2 cm from the bracket base. The custom bases were then rinsed thoroughly with tap water and cleaned with alcohol pads.

Chairside step: Porcelain surface preparation and bracket delivery

Mechanical fine bur (8850KR, Brasseler Canada, Montreal, Quebec) roughening was done lightly to remove the porcelain glaze, until a matte surface was noticeable. Porc-Etch (Reliance Orthodontic, Itasca, Illinois) containing 4% HFA was left for 2 minutes, then rinsed thoroughly with water and dried. The porcelain surface was verified to obtain a frosty white look. Silane or porcelain conditioner (Reliance Orthodontic, Itasca, Illinois) was applied for 60 seconds then air dried. Two coats of the all-purpose bonding primer Assure (Reliance Orthodontic, Itasca, Illinois) was applied generously, and the last coat was dried lightly to evaporate the solvent. Assure does not need to be dried completely according to the manufacturer. Polymerization was not necessary in any of these steps.

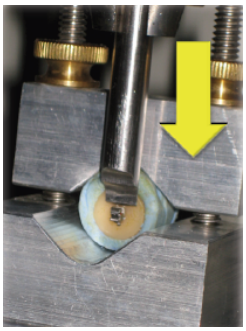
Brackets were bonded manually to each porcelain surfaces using Sondhi A+B Rapid Set (3M Unitek, Monrovia, California). A constant force application of 250 grams was applied with a tension gauge (CORREX, Koneiz, Switzerland). The adhesive was allowed to cure according to manufacturer's recommendations. The force was held for 30 seconds, and the bracket was left undisturbed for an additional 2 minutes. Large flashes of adhesive were carefully removed with an instrument afterwards (SC13/146, Hu-Friedy, Chicago, Illinois).

EXPERIMENTAL TESTING:

Experiment Part I: Shear bond testing

Samples were stored in an incubator at 37º Celcius, submerged in distilled water for 24 hours, then thermocycled (Sepras, Model BT-15, Repentigny, Quebec) according to the ISO 11405 recommendation. Each specimen underwent 500 complete cycles in distilled water baths at 5º and at 55º degrees Celsius. Every cycle lasted 75 seconds, with 30-second dwell-time for each bath seperated by 15 seconds of transfer-time between baths. Each

specimen was then tested with a universal testing machine (5900 Series, Instron, Norwood, Massachusetts). The acrylic cylinder samples were positioned into the Instron machine so that the loading blade could move as closely as possible to the bracket-porcelain interface to recreate an adhesive fracture and provide an ideal shearing force, at a rate of 0.1 mm/min (Figure 3). The maximum load was recorded with the BlueHill2 Software (Instron, Norwood, Massachusetts). Shear bond strength was calculated according to the surface area of the bracket base of 12.0 mm^2, provided by the manufacturer.



Article Figure 3: Universal testing machine in shear compression mode where the blade is placed as closest to the bracket-porcelain interface as possible. (Image courtesy of Dr. Stephanie H. Mai, Université de Montréal)

Experimental part II : Microscopic examination

Debonded brackets and their corresponding porcelain discs were examined and photographed using a Scanning Electron Microscopy (JEOL JSM-6460LV, Peabody, Massachusetts), under low vacuum mode at 20KV. A score from the modified adhesive remnant index (ARI) was given to each porcelain disc according to the chart detailed in Figure 4: 0 = no adhesive on the porcelain surface, 1 = less than 50% of the adhesive remained on the porcelain surface, 2 = more than 50% but less than 100% of the adhesive remained on the porcelain, 3 = 100% of the adhesive was left on the porcelain surface, leaving the bracket's mesh-pad imprint, 4 = fracture or damage to the porcelain. An inter-

evaluator test was completed by an external evaluator on 5 random scanning electron microscopy (SEM) photos from each experimental group, for a total 30 SEM photos.

Statistics

Statistics were performed on ranks of SBS since data was not normally distributed. Data presented as median (mininum value – maximum value) Thus ranks were used to normalize the distribution. The following tests were performed: a two-way ANOVA with two independent variables, mechanical and chemical preparations, and a one-way ANOVA, comparing the 6 groups individually with each other. The following tests were done on collected ARI scores. A Kruskall-Wallis evaluated the ARI scores' distribution across the tested groups. Mann Whitney U tests were used for pairwise comparisons of ARI scores from each group. P values from pairwise comparisons were adjusted with the method of Tukey. Focus was placed on identifying whether the porcelain was irreversibly damaged or not. A Weibull analysis was also performed to determine bond reliability at specific loads of 7.8 MPa, as recognized by Reynold's standards.[60] Reynold's standard is the minimum bond strength required in a clinical setting for orthodontic tooth movement, shown to be 5.9 to 7.8 MPa. A Kappa test was done to measure of agreement between evaluators. SPSS 20 and Systat 13 were used for statistical analyses. A Kappa of 0.81 shows a very good agreement of ARI scoring between evaluators.

RESULTS

One sample was lost in the process in group (+ Bur + HFA) during the thermocycling step. The SBS values for each experimental group are listed in Table 1. The medians ranged from 17.0 (13.3 - 21.4) MPa to 26.7 (0.0 – 30.0) MPa, obtained in the group (- Bur + HFA) and in the group (- Bur + HFA + S) respectively. The median SBS obtained in this study for all 6 groups are greater than the force required for orthodontic tooth movement (OTM) per Reynold's classic standard of 7.85 MPa [60], and are hence all surface preparations were clinically adequate for OTM.

Brackets bonded to porcelains dics treated with (- Bur + HFA) had statistically significant lower SBS than discs treated with (- Bur + HFA + S), (- Bur + S + P), (+ Bur + HFA + S), (+ Bur + S + P), ($p<0.05$, one-way ANOVA). However, SBS for group (- Bur + HFA) was not significantly different from SBS for group (+ Bur + HFA). Furthermore, the SBS for group (+ Bur + HFA) was not significantly different from the other 4 groups.

Article Table 1: Shear Bond Strength Results

Group / SBS (MPa)	- Bur + HFA *	- Bur + HFA + S	- Bur + S + P	+ Bur + HFA *	+ Bur + HFA + S	+ Bur + S + P
Mean ± SD	17.7 ± 2.6	24.0 ± 7.4	23.3 ± 3.5	20.1 ± 4.8	23.6 ± 4.7	23.3 ± 8.8
Median	17.0	26.7	23.9	20.3	24.8	26.2
Minimum	13.3	0.0	13.9	6.6	9.3	2.6
Maximum	21.4	30.0	28.1	28.1	29.3	32.5

** SBS of (-Bur + HFA) group was shown to be significantly lower, with $p<0.05$ according to the one-way ANOVA, than (- Bur + HFA + S), (- Bur + P + S), (+ Bur + HFA + S) and (+ Bur + P + S).*

** SBS of (+ Bur + HFA) was not significantly different from the other groups' SBS.*

The two-way ANOVA showed that mechanical preparation (fine diamond bur roughening) did not significantly affect the SBS ($p= 0.31$). The elimination of a mechanical preparation

step can facilitate the chairside delivery of orthodontic brackets, reducing the amount of instrumentation and allowing faster chair set-up and clean-up in between patients. Among the 3 different chemical preparation combinations tested, only SBS of HFA application alone (- Bur + HFA) was significantly lower when compared to other chemical preparations tested ($p < 0.05$, two-way ANOVA).

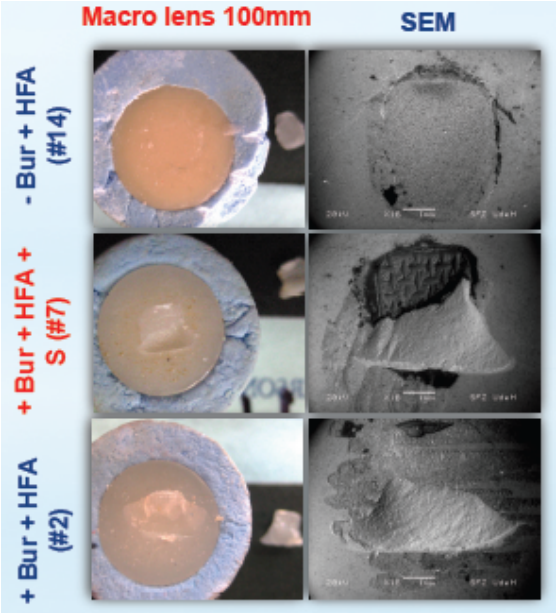
Table 2 shows the results of ARI scores. Independent samples Kruskall-Wallis analysis showed that ARI distribution was not the same accross the 6 groups. Furthermore, a Mann Whitney U pairwise comparison revealed that ARI scores for the group which received no mechanical preparation but was treated with hydrofluoric acid was significantly lower than the ARI scores of all other other groups ($p < 0.001$). This means that ARI scores for group (- Bur + HFA) were statistically significant different from the other 5 groups tested. An extremely high percentage of porcelain damage, ranging from 80 – 100% of the samples, can be noted in all groups except for the group treated with only HFA (- Bur + HFA) in which only 6% of the samples were fractured.

Article Table 2 : Modified Adhesive Remnant Index Results

Group / ARI	- Bur + HFA *	- Bur + HFA + S	- Bur + S + P	+ Bur + HFA	+ Bur + HFA+ S	+ Bur + S + P
Median	0	4	4	4	4	4
Minimum (#discs)	0 (14)	4 (0)	2 (1)	0 (1)	4 (0)	2 (3)
Maximum (#discs)	4 (1)	4 (15)	4 (14)	4 (13)	4 (15)	4 (12)
Total #discs	15	15	15	14	15	15
% damaged discs	6.7	100	93.3	92.9	100	80.0

** ARI scores for (-Bur + HFA) were significantly different from other groups' ARI scores ($p<0.001$, Mann Whitney U pairwise comparison), while these other 5 groups were not significantly different from each other.*

Figure 4 shows samples after shear testing; one can see the extent of inesthetic damage in the porcelain.



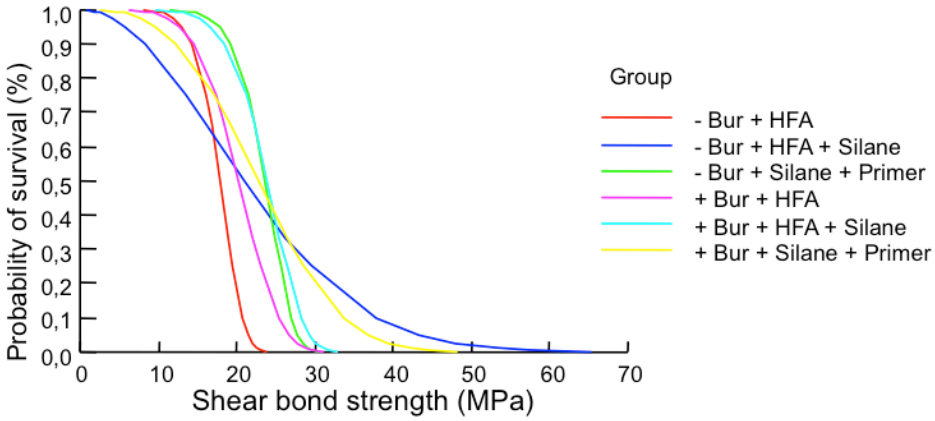
Article Figure 4: Three random samples' surface condition post-testing. Left column: photo taken with a macro lens Canon 100mm; Right column: scanning electron mircroscopy photo of the undamaged and damaged porcelain surfaces; Top sample: ARI score of 1; Middle sample: ARI score of 4 due to unesthetic and most likely unrestorable porcelain surface; Bottom sample: ARI score of 4.

Four experimental groups out of six had at least one sample that was below OTM standards. The Weibull analysis, Weibull modulus, characteristic strength results, probabilities of bracket failure and the percentage of bracket survival when shear forces of 7.8 MPa are applied to the brackets are included in Table 3.

Article Table 3: Weibull Results

Group	Weibull modulus (β)	Characteristic strength (α)	Shear bond strength (MPa) at 10% probability of failure	Shear bond strength (MPa) at 90% probability of failure	% of bracket survival at 7.8 MPa
- Bur + HFA	8.1	18.8	14.2	20.8	99.9
- Bur + HFA + Silane	2.0	25.0	8.2	37.9	90.9
- Bur + Silane + Primer	9.1	24.6	19.2	27.0	100.0
+ Bur + HFA	5.5	21.8	14.4	25.4	99.6
+ Bur + HFA + Silane	7.2	25.2	18.5	28.3	100.0
+ Bur + Silane + Primer	3.0	25.6	12.3	33.7	97.4

Figure 5 shows the probability curve from the Weibull analysis of orthodontic bracket survival rates. Survival rates decrease as SBS increases. There is at least 90.9% chance of bracket survival at the standard recommended force of 7.8 MPa for OTM in all 6 groups tested.



Article Figure 5: Probability (0-1) of bracket survival at respective bond strengths.

Therefore, it can be stated that the first hypothesis holds partly true: chemical treatments did significantly alter the shear bond strength of metal brackets bonded to leucite-reinforced porcelain surfaces when silane alone or in combination with primer was involved. However, the second hypothesis is rejected: mechanical treatments did not alter shear bond strength. The third hypothesis is rejected, since the various surface preparations tested affected how the porcelain will fracture at debonding.

DISCUSSION

Shear Bond Strength Comparisons:

It was observed that SBS values from indirect bonding to porcelain obtained in this study are in agreement, if not of higher values, than recent publications' reported SBS for indirect bonding to teeth under similar testing conditions (same composite and adhesive resin system). In Daub et al. and Klocke et al.'s studies on extracted teeth, metal orthodontic brackets bonded with TXT and SD have a mean SBS of 12.3 MPa and 14.1 MPa respectively.[20, 54]

As this is the first shear bond strength study on indirect bonding of orthodontic brackets to porcelain in the literature, there are no values to compare the results with. Shear bond strength values will be compared with results from direct bonding studies of orthodontic brackets to porcelain. The means from this study ranged from 17.7 MPa up to 24.0 MPa, and were found to be more than adequate for OTM. Similar results or even weaker mean SBS were also found in recently published studies where direct bonding methods were tested.[33, 36, 77] Schmage et al.'s study on direct bonding with unspecified ceramic discs with the self-curing Concise composite & adhesive resin system (3M Dental, Monrovia, California) after surface preparation combinations with (5% HFA) and with (5% HFA + S) and 5000 cycles of thermocycling provided mean SBS values of 14.7 MPa and 12.2 MPa respectively.[36] Turk et al.'s direct bonding with TXT in their group of (9.6% HFA + S) had a mean SBS of 5.39 MPa with feldspathic samples.[67] This was less than optimal, and was not significantly lower when compared to their group (9.6% HFA + S) at 11.11 MPa with lithium-disilicate ceramic samples. No porcelain fractures were found in these two studies. Sant'Anna et al. studied feldspathic porcelain dics and direct bonding with Concise composite & adhesive resin system (3M Dental, Monrovia, California) followed by 500 cycles of thermocycling.[77] No significant difference among all four groups tested were found. Their group treated with (- Bur + 10% HFA + S) had a mean

SBS of 16.2 MPa. With a comparable mean SBS, their other group treated with (+ Bur + S) obtained a mean SBS of 17.11 MPa without any etching. Larmour et al.'s direct bonding study with Transbond composite resin (3M Dental, Monrovia, California) on porcelain denture teeth found that their group of (- Bur + 9.6% HFA + S) provided an impressive mean SBS value of 103.2 MPa.[33]

IPS Empress ceramic discs are hot-pressed leucite-reinforced ceramic discs like the Finesse All-Ceramic discs used in this study. Karan et al. studied the direct bonding system TXT on various types of ceramics (feldspathic, leucite-based IPS Empress and lithia-disilicate-based IPS Empress 2).[32] When bonding to the IPS Empress samples, the groups treated with (Al_2O_3 + 9.6% HFA) and (Al_2O_3 + 9.6% HFA + S) obtained mean SBS of 14.7 MPa and 9.9 MPa respectively after 500 cycles of thermocycling. Silane did not enhance SBS in this case. When IPS Empress samples were not etched, and treated only with (Al_2O_3 + S), they also obtained a comparable mean SBS of 12.3 MPa. Abu Alhaija et al. tested direct bonding with TXT to IPS Empress crowns after 24hr storage in distilled water at room temperature. Their (9.6% HFA) group obtained a mean SBS of 67.4N, which is higher than Tava and Watt's minimally recommended bond strength for OTM of 58N. The IPS Empress group had significantly lower SBS than the other tested groups of In-Ceram and conventional (feldspathic) ceramics after receiving the same surface treatement. There were few porcelain fractures in this study, and none were among the IPS Empress samples.[68]

In this study, mechanical preparation with a fine bur did not enhance SBS. Other authors have found the same, concluding that bur roughening is generally unecessary for OTM while risking unacceptable damage to the porcelain surface.[33, 49] Abu Alhaija et al.'s study did not involve any bur roughening or primer application, and all the groups were tested with acid etching and provided sufficient bond strength for OTM.[27] Turk et al.'s study found that their mechanical preparation with various aluminium oxide sandblasting, with 25 and 50 um, when compared to various bur roughening, only made a

significant difference in SBS in the feldpathic ceramic groups, and not for their lithium disilicate ceramic group.[67]

In this study, silane significantly enhanced adhesion. The tested group (- Bur + HFA) had a significantly lower SBS than the group (- Bur + HFA + S). Perhaps without any mechanical preparation, silane is required to boost the adhesion by providing chemical bonds. The study also reveals no statistically significant difference in SBS between groups treated with (- Bur + HFA + S) and (- Bur + S + P)'s. These results suggest that (- Bur + HFA + S) surface preparation provided a similar adhesion as the group (- Bur + S + P). Hydrofluoric acid etching and silane application is a very popular suggested method of porcelain conditioning. Therefore, the findings suggest that silane and primer application can be considered as an alternative to the popular protocol involving HFA and silane. Eliminating HFA would allow a clinician to avoid the risks of soft tissue burns associated with the use of this toxic product, yet still obtain a comparably high bond strength.

Ceramic Fracture Comparison :

Unlike for the group (- Bur + HFA), the other 5 groups in this study showed a disappointingly high incidence of porcelain fractures after debond ranging from 80% and higher. In Sant'Anna et al.'s study with feldspathic porcelain, groups treated with (- Bur + 10% HFA + S) and (+ Bur + S) had 54% and 68% respectively in porcelain fractures.[77] In Larmour et al.'s study, 35% of the group treated with (- Bur + HFA + S) had visible porcelain surface damage at debond, which is considered high by the author.[33] Karan's comparison between feldspathic, leucite-reinforced and lithium disilicate ceramics showed that the leucite-reinforced ceramic group had the highest incidence of 18% of cohesive fractures when compared to the others.[32]

In clinical practice, the incidence of ceramic damage while debonding was stated to be very low or not to occur at all, and to be independant of the bonding method.[48] The reason why *in vitro* studies obtain higher numbers of porcelain damage is that clinically

proper safe debonding techniques with adequate peeling forces are not well reproduced in laboratory shear testing.[78] The extremely high fracture incidence found in this experiment may also be due to several factors. Certain types of ceramic tested, such as the leucite-reinforced porcelain of this study, are more susceptible to debonding fractures and that fractures seem to occur more when silane was applied.[32] Similarly, other investigators have found that silane can increase SBS to the point of cohesive fractures at debonding.[33, 36, 48] The composite resin may also have contributed to increasing bond strength, since it tends to offer a better adhesion than resin modified glass-ionomer cements (RMGICs).[33, 36, 48]

The Weibull analysis is used as a survival analysis tool, and can provide more clinical relevant information. A high survival rate in the mouth of any adhesive system is probably more important clinically than a high mean SBS. Similarly to our results of survival rate of 90.9% or greater at 7.8 MPa, Daub et al. found that teeth bonded indirectly with TXT and SD scored a 92.1 % survival rate at 7.8 MPa after 500 cycles of thermocycling.[54] In fact, this study's Weibull survival rates agree more with the reported bond failure rates of Miles and Weyant's clinical trial on indirect bonding at 4.5 % over 3 months, and 6.5-13.9 % over 6 months period.[57] The Weibull analysis can hence provide a better indication of the adhesion trend.

Experimental considerations :

Limits of the study include : testing Finesse All-Ceramic Ingots only (Dentsply GAC, Bohemia, New York), the use of one composite resin for custom base fabrication and one indirect bonding adhesive resin system, the use of one type of metal orthodontic bracket and finally the testing at a relatively slow crosshead speed that can unfortunately propagate surface micro-cracks into the porcelain. Thermocycling studies also have limits. Aging in water generally decreases bond strengths, but not to catastrophic values and thermocycling in water poorly represents the dynamic environment of the oral cavity.[29]

There is important variability in the methods used to evaluate bond strength within the orthodontic literature, partially due to the lack of standardization protocols. As a result, it is difficult to draw any meaningful conclusion when comparing studies.

Future reseach venues can be oriented towards alternative debonding methods should be explored using manual debonding, electrothermal debonding devices and lasers.[79-81]. *In vitro* experiments should include a Weibull analysis and probability rates of brackets survival as they are relevant for extrapolating laboratory results into a clinical setting. Furthermore, orthodontic materials that perform well in *in vitro* experiments should always be tested with *in vivo* randomized clinical trials.[82]

CONCLUSION

Median SBS obtained from all 6 porcelain surface treatments exceed the force required for OTM. From this study, several conclusions can be reached when considering indirect bonding of metal brackets to leucite-reinforced porcelain with composite resin custom bases and a chemically-cured adhesive resin:

1. Chemical treatments can significantly alter shear bond strength, especially when silane is involved.
2. Mechanical bur roughening does not enhance shear bond strength when chemical treatments of hydrofluoric acid, silane or primer application were involved.
3. The way porcelain surfaces are prepared affects how the porcelain fractures at debonding.
4. To avoid the use of hydrofluoric acid, a combined application of silane followed by primer application on the porcelain surface is clinically attractive and safe, while providing great adhesion strength. Although the percentage of porcelain fracture following debonding in this *in vitro* study is very high, the real incidence of porcelain fracture is reported to be low in a clinical setting. An operator's debonding method is technically different and safer. It is however still wise to warn the patient that there is a risk of porcelain fracture when brackets fail or are removed.
5. Until more clinical data is available to support the low risk of porcelain fracture after manual debonding, the recommended porcelain surface treatment protocol when bonding indirectly metal brackets is the use of hydrofluoric acid etching alone. This will provide more than sufficient strength for orthodontic tooth movement. However, careful handling of the acid is critical to avoid burns of soft tissues: either the staff is properly trained to handle such products when indirect bonding is delegated to them or the orthodontist takes over the task of chairside bracket delivery in these situations.

5. DISCUSSION

5.1 Comparaisons of Results

Ideally, a balance is desired between maximum bond strength for efficient orthodontic tooth movement, avoiding emergency bracket failures due to poor adhesion, and minimum risk of irreversible and unesthetic damage to ceramic restorations at the end of the orthodontic treatment. The ideal clinical protocol would be quick and efficient, not technique sensitive for a humid oral environment, and safe for the patient and staff. Therefore, an easy and predictable chairside protocol is required to reduce the potential complications before, during and after bonding.

5.1.1 Shear Bond Strength

As stated in the article, results from this *in vitro* experiment are in agreement with the current literature.

In this study, silane significantly enhanced adhesion. The findings from this experimental study also suggest that silane and primer application can be considered as an alternative to the popular protocol involving HFA and silane, thus avoiding use of the toxic material.

A similar recommendation was made by Sant'Anna et al. These authors concluded that silane and composite alone may be adequate for bonding to porcelain, as their samples provided a mean SBS of 17.7 MPa.[77] This may be due to silane's strong ability to chemically bond to porcelain, allowing the acid etching (or any mechanical preparation) step to be skipped. Silane is a bonding agent, commonly referred to as a porcelain conditioner. It has a general chemical structure $R'—Si(OR)_3$, where R' is the organofunctional group, typically a methacrylate, that reacts to the adhesive system by creating a covalent bond. The alkyl group (R) is hydrolyzed to a silanol (SiOH), creating another covalent bond with the silicon inorganic particles (Si—O—Si), completing the bonding process to the ceramic material.[4]

However, theses results are not in agreement with Schmage et al. and Karan et al.'s findings. Schmage et al.'s test groups (5% HFA) and (5% HFA + S) did not show any significant bond strength increase after 5000 cycles of thermocycling. The authors suspect that thermocycling canceled the added strength of silane.[36] Laboratory thermocycling by plunging testpieces between distilled water baths at 0◦-60◦ Celsicus causes amplified thermal shocks as the surface layer expands or contracts over the bulk of material which remains unchanged.[29] In Karan et al.'s study, silane did not enhance SBS significantly. In fact, in some groups, silane application yielded lower mean SBS. Therefore silane does not seem to provide additional advantages in a predictable way.

5.1.2 Adhesive Remnant Index & Fractures

As stated in the article, results from this *in vitro* experiment appear to show greater severity and less desirable results than the current literature.

In clinical practice, the incidence of ceramic damage while debonding was stated to be very low or not to occur at all, and to be independant of the bonding method.[48] The reason why *in vitro* studies obtain higher numbers of porcelain damage is that clinically proper safe debonding techniques with adequate peeling forces are not well reproduced in laboratory shear testing.[78] In shear testing, the brackets are loaded by a blade in compression so that the brackets slide in a parallel fashion off the substrate. It was also reported that when SBS of ceramic bonded with composite resin was higher than 13 MPa, there is a risk of cohesive fractures.[62]

Unlike the (- Bur + HFA) group, the other 5 groups in this study showed a disappointingly high incidence of porcelain fractures after debond ranging from 80-100%. In Sant'Anna et al.'s study with feldspathic porcelain, groups treated with (- Bur + 10% HFA + S) and (+ Bur + S) had 54% and 68% respectively in porcelain fractures.[77] In Larmour et al.'s study, 35% of the group treated with (- Bur + HFA + S) had visible porcelain surface damage at debond, which is considered high by the author.[33] Karan's

comparison between feldspathic, leucite-reinforced and lithium disilicate ceramics showed that the leucite-reinforced ceramic group had the highest incidence of 18% of cohesive fractures when compared to the others.[32]

This disappointing observation may be due to several factors. Certain types of ceramic tested, such as leucite-reinforced porcelain in this study, are more susceptible to debonding fractures.[32] Although the incidence is not comparable, Karan et al.'s leucite-reinforced groups also displayed the highest incidence of porcelain damage in the study. The same authors also noted that fractures seem to occur more when silane was applied. Similarly, other investigators have found that silane can increase SBS to the point of cohesive fractures at debonding. [33, 36, 48]. As suggested by authors, a cohesive fracture of the ceramic may imply that the bond strength between the adhesive or composite resin and the ceramic was stronger than the ceramic itself.[83] Too much of a strong bond can be blamed, as well as the weakening of the porcelain structure if roughening of the porcelain surface was performed. Micro-cracks can develop and cause the cohesive fractures.[77] If this is true, then silane may actually be counterproductive.

The composite resin may also have contributed to increasing bond strength, since it tends to offer a better adhesion than resin modified glass-ionomer cements (RMGICs). This is in fact supported by Larmour et al.'s results in which RMGICs such as Fuji Ortho L.C (G.A.C. Corporation, Tokyo, Japan) had significantly lower SBS than the composite groups when all other conditions were the same.[53] The authors also found that samples bonded directly with composite resin had the greatest amount of porcelain facture, ranging from 35-40% of the groups.

Another contributing factor may be the testing methodology. The velocity at which the crosshead of the Instron Universal Testing Machine travels may have an impact on how the micro-fractures propagate inside the porcelain structure. In reality, when accidental debonds occur, it occurs more quickly than the 0.1-1.0 mm/min speed commonly used in the laboratory setting. Eliades et al. state that a slow speed of the crosshead may allow

progressive propagation of micro-fractures present initially or introduced by the surface roughening procedures.[59]

5.2 Clinical Implications

The data from our study shows that mean and median SBS values from all 6 surface preparation groups are adequate for clinical application and OTM, based on Reynold's and Rossouw's standards.[56, 60] *In vitro* and *in vivo* testing has showed similar bond strength for both direct bonding method and indirect bonding method on teeth.[7, 15, 16, 54, 57, 63, 64] However, there is always less control of a clinical environment than in an ideal experimental setting, especially due to the numerous steps. In the case of bonding to porcelain and of indirect bonding, there are even more additional steps involved.

In vitro bond strength testing is valuable for initial screening and selection of materials, but it cannot be viewed as a substitute for *in vivo* testing. Therefore one must be cautious when attempting to extrapolate *in vitro* results into clinical settings. *In vivo* stresses are difficult to recreate in an *in vitro* set-up, such as activated archwire forces combined with occlusal forces, extreme temperatures, pH changes, variable microbial flora and its bi-products.[59] Matasa et al. states that these factors have to be kept in mind as they have been known to alter the structure and surface properties of dental materials used to restore teeth.[84] Indeed, Eliades et al. consider these factors, which are hard to study, crucial as they propagate chronic fatigue and stress from microbial infiltration of the composite resin into permanent microscopic fissures and evolve into macroscopic fissures. Eventually, all this cascade progresses towards failure.[59, 85] Thermocycling only recreates temperature changes.

Therefore, orthodontic materials that perform well in *in vitro* experiments should always be tested with *in vivo* randomized clinical trials.

5.3 Limitations of the Study

In a clinical setting, operators do not generally know what type of porcelain they are bonding to. The study was limited to one type of porcelain and from one particular manufacturer, Finesse All-Ceramic leucite-reinforced ceramic discs (Dentsply GAC, Bohemia, New York). Feldspathic porcelain should be included among the test groups as it is employed in porcelain-fused to metal crowns, which have been for long the most common ceramic restoration. Although leucite-reinforced ceramics resemble most feldspathic porcelain in terms of composition, surface porcelain treatments used in this study may not provide similar results if performed on other types of ceramics. The Finesse All-Ceramic discs colors A3 and A4 used in this study were a donation from the Laboratoire Bourque & Robert (Montréal, Québec). If more funding was available, testing with other more updated all-ceramic materials can be helpful to further understand how various surface treatments can affect SBS.

Only one composite resin material for custom base fabrication and only one indirect bonding adhesive resin system was studied. Other products with different polymerization reactions may be of interest as more and more clinicians are bonding indirectly, such as chemically-cure Maximim Cure and Custom I.Q. (Reliance Orthodontics, Itasca, Illinois).

Another limitation was that only one type of metal orthodontic bracket was tested; it is a relatively small single bracket with a small bracket base surface area for adhesion. Testing with different bracket topography can also potentially provide various levels of bond strength. Bishara et al. also found that bonding brackets does not require silane application as the new bracket base designs achieve adequate bracket retention simultaneously allowing its removal without damage.[70]

The crosshead speed used in this study can be too slow to replicate *in vivo* debonding. When accidental *in vivo* debonding of brackets occurs, it occurs with a greater force, and at a greater speed, than when compared with *in vitro* settings which are usually

set at lower speeds of 0.1 to 1.0 mm/minute. At low cross-head speeds, the viscoelasticity of the composite is more pronounced than in real clinical situations.[59]

Thermocycling studies also have limits and bond strength loss is time-dependant. Aging in water generally decreases bond strengths, but not to catastrophic values. Likewise, many samples survive thermocycling even with a reduced bond strength.[29] Thermocycling in water poorly represents the dynamic environment of the oral cavity in which there is saliva, food and beverages with varying acidities. As previously mentioned, Eliades et al. state that *in vivo* stresses are difficult to mimic in a laboratory setting.[59]

5.4 Future Research Venues

The approach would be to find a porcelain surface treatment that would provide SBS within the optimum range between 7.8 MPa and 13.53 MPa when bonding indirectly with the composite resin material of interest. While 7.8 MPa is the reported standard for OTM, 13.53 MPa is the limit value where the risk of cohesive fracture increases.[62]

Since all of the surface preparations of this study provided sufficient adhesion for OTM, the focus should be to further reducing porcelain surface fractures. Future laboratory testing can involve removing an agent, such as silane. The use of silane can be long and uncomfortable for the patient, as the clinician must apply several generous coats of silane and wait for the agent to dry before continuing the chairside manipulations. Testing can also focus on surface preparation combinations around the primer Assure (Reliance Orthodontics, Itasca, Illinois). Crosshead velocity should be set at a higher speed than the one used for this study to better replicate true clinical debonding.

Alternative debonding methods should be explored. Studies comparing machine debonding and manual debonding can be interesting, especially to compare the percentage of porcelain damage after bracket removal. Debonding with electrothermal devices and lasers have also been initiated.[79-81]. These methods have previously been shown to help

reduce the risk of shattered porcelain during debonding while posing little risk of pulpal damage.

Lasers have become increasingly popular and it is possible that orthodontists may have acquired a unit to do adjunctive procedures such as periodontal interventions in their office. According to Tocchio et al., laser energy can degrade resins either by thermal softening, thermal ablation, or photoablation.[79] In thermal softening, the laser heats the bonding agent until it softens. Thermal ablation occurs when the quick rise in temperature brings the resin into its vaporization range; thermal softening follows and allows debonding. Photoablation results in the bracket's being blown off the tooth surface. Thermal softening is a relatively slow process, increasing the risk of a large temperature rise within both the tooth and the bracket. Thermal ablation and photoablation proceed rapidly, therefore there is very little heat diffusion and the tooth and the bracket stay near physiologic temperatures. Some authors demonstrated very promising advantages in using lasers for orthodontic bracket removal: it was found that time spent to debond ceramic brackets is reduced, debonding forces are significantly reduced, and the risk of enamel damage and bracket fracture is also significantly reduced. Indeed, Azzeh et al. found that the carbon dioxide (CO_2) super-pulse laser is superior to normal pulse CO_2 and yttrium aluminum garnet (YAG) lasers.[80] These *in vitro* studies have only been performed on extracted teeth.

Mean SBS may not be the best performance indicator for evaluating bonding materials and methods since it considers extreme values. It may be better to report median SBS. Alternatively, emphasis can be placed on the weaker values in a distribution of SBS results as they can be clinically important and can result in clinical debonding of brackets.[55]

The greatest problem in shear bond testing protocols is their lack of consistency in methodology making the task of comparing results impossible. Unfortunately, no specification from the International Organization for Standardization, American National

Standard Institute or the American Dental Association currently exists to standardize testing protocols. Therefore ISO standards must be set and followed rigourously in future studies. Furthermore, *in vivo* research in the form of randomized clinical trials on the effectiveness of indirect bonding is needed to evaluate the true clinical success of any bonding method and product. This may be challenging as only a minor percentage of the orthodontic population have ceramic restorations, and a clinical trial would require an extensive sample population to make a significant conclusion. In the mean time, presenting Weibull analysis and probability rates of survival of brackets with *in vitro* experiments can be relevant for extrapolating laboratory behavior into a clinical setting, after accounting for the caveats noted previously.

6. CONCLUSION

The median of SBS obtained in all 6 porcelain surface preparations exceeded the force required for orthodontic tooth movement according to Reynold's classic standards of 7.85 MPa.[60] The following are recommendations to consider when bonding metal brackets to leucite-reinforced porcelain with composite resin custom bases and a chemically-cured adhesive resin via an indirect method:

1. Chemical treatments can significantly alter the shear bond strength, especially when silane is involved.
2. Mechanical bur roughening does not enhance shear bond strength when chemical treatments of hydrofluoric acid, silane or primer application were implicated.
3. Different protocols of porcelain surface preparations affect how porcelain fractures at debonding.
4. If one wants to avoid the use of hydrofluoric acid, a combined application of silane followed by primer application on the porcelain surface is clinically attractive and safe, while providing great adhesion strength. Although the percentage of porcelain fracture following debonding in this *in vitro* study is very high, the reported incidence of porcelain fracture is actually low in a clinical setting because the operator's debonding method is technically different and safer. It is however still wise to warn the patient that there is a risk of porcelain fracture when brackets fail or are removed. An attempt to answer this question would be to conduct *in vitro* studies that compare the incidence of porcelain fractures after debonding with a universal testing machine in shear compression mode versus the incidence of porcelain fractures after manual debonding with a pure shearing technique. This would drastically help clinicians determine the relevance of the fracture findings from *in vitro* studies. Indeed, this type of *in vitro* study should include different porcelains available on the market and include different

adhesive and composite resin systems after a thermocycling step. Otherwise, *in vivo* studies with randomized patients bonded indirectly with different adhesive systems can be conducted to track the incidence of clinical porcelain damage and the extent of patient disatisfaction at the end of their orthodontic treatment. In the mean time, it is wise to warn the patient that there is a risk of porcelain fracture when brackets fail or are removed.

5. Until more clinical data is available to support the low risk of porcelain fracture after manual debonding, the recommended porcelain surface treatment protocol when bonding indirectly metal brackets is the use of hydrofluoric acid etching alone. This will provide more than sufficient strength for orthodontic tooth movement. However, careful handling of the acid is critical to avoid burns of soft tissues. Either the orthodontist must train their orthodontic staff to properly handle such products if indirect bonding is delegated to them or the orthodontist should take over the task of chairside bracket delivery in these situations.

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Appendices

APPENDIX 1

Thomas' 1979 original list of advantages and disadvantages for indirect bonding.

ADVANTAGES
1. Allows more accurate placement of brackets 2. Decreases chair time of appliance placement from 2-3 hours to 25-45 minutes 3. Less patient discomfort, separators for bands is no longer necessary 4. Interproximal caries can be detected more readily and restored if necessary with no bands in the way 5. Reduces risk of caries and decalcification as they are possible under bands, especially loose bands 6. Esthetically more pleasing 7. Improved tissue health during treatment 8. Diagnostic considerations (extraction or non-extraction) 9. "Sealant" placed on labial and buccal surfaces ; "preventive" in nature 10. Occlusion - what you see is what you get- Minimal settling in bonded treatment 11. Party erupted teeth can quickly be brought under control. No need to wait for full eruption to cement band 12. Immediate retainers may routinely be made 13. Reduces costly band inventory 14. New technique or appliances may be tried without costly inventory 15. Overall better placement acceptance related to esthetics and ease of placement.
DISADVANTAGES
1. Teeth with crowns, large buccal restorations or acrylic restorations will not bond 2. Sometimes difficult on very short clinical crowns 3. Correct technique must be followed closely 4. Those fearful of change will likely be reluctant to try the technique

APPENDIX 2

Sondhi™ Rapid-Set Indirect Bonding packaging.

Convenient, functional packaging.

3M Unitek's comprehensive treatment approach encompasses the packaging itself. A functional kit box that incorporates the Sondhi indirect technique was the driving design principle. The kit comes packaged in a large light-tight container, which can be used to store the models before curing.

The kit includes a bottle of Resin A and Resin B adhesive, two different applicators (one for each resin), plus disposable tips. The applicators and adhesive bottle caps are color-coded for your convenience, one is white, the other orange. The kit can be ordered with or without a videotape that guides you step-by-step through the procedure.

Ordering Information.

Sondhi™ Rapid-Set Indirect Adhesive Kit with Technique Video (1) 10ml bottle Resin A, (1) 10ml bottle Resin B, (2) Brush Holders (1 orange, 1 white), (60) Brush Tips, (1) 2-cavity Dispensing Well, (1) VCR Tape, (1) Instruction Booklet	712-071

Sondhi™ Rapid-Set Indirect Adhesive Kit (1) 10ml bottle Resin A, (1) 10ml bottle Resin B, (2) Brush Holders (1 orange, 1 white), (60) Brush Tips, (1) 2-cavity Dispensing Well, (1) Instruction Booklet	712-070

Reorder Items

10ml bottle Resin A	712-072
10 ml bottle Resin B	712-073
Mixing Wells (4), 2-cavity	712-074
Light-Tight Box	712-075
Indirect Bonding Technique Video VHS/NTSC (PAL and SECAM videos also available.)	6600-330
Indirect Bonding Technique CD Version	012-147

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APPENDIX 3

Material Safety Data Sheet

Issued: 7/22/2009 **Version Number: 6**

1. Identification of Substance/Preparation and Company/Undertaking

Product Name: Porc-Etch (Porcelain Etchant)
Manufacturer: Reliance Orthodontic Products, Inc. 1540 West Thorndale Ave, Itasca, IL 60143 USA
Emergency Telephone: 630-773-4009 Fax: 630-250-7704
Authorized Representative:
Emergo Europe, Molenstraat 15, 2513 BH The Hague, The Netherlands
Telephone: +31-70-345-8570 · Fax: +31-70-346-7299

CE Administrator: Amtac Certification Services Ltd., Davey Avenue, Knowlhill, Milton Keynes, MK5 8NL, United Kingdom

2. Composition/Information on Ingredients

Ingredient	Concentration Range (%)	CAS Number	Symbol/Risk Classification	OSHA PEL (mg/m3)	ACGIH (mg/m3)	LD50 (mg/kg, rat/oral)
Hydrofluoric Acid	4	7664-39-3	T,C,R23/24/25-34	3ppm	3ppm	N/D

3. Hazards Identification

Toxic and Corrosive. Toxic by inhalation, in contact with skin and if swallowed. Causes Burns.

4. First-aid Measures

Inhalation: Provide fresh air and rest immediately.
Skin Contact: Wash immediately with soap and water.
Eye Contact: Flush immediately with running water for at least 15 minutes while keeping eye lids open; seek medical attention immediately.
Ingestion: Drink two glasses of water or milk. Seek medical attention if a substantial amount has been ingested.

5. Fire-fighting Measures

Fire-fighting media: Dry chemical powder, foam or carbon dioxide.
Fire and explosion risks: Upon heating, irritating or toxic gases may form.

6. Accidental Release Measures

Personal Precautions: Prevent skin/eye contact, Provide ventilation.
Environmental Precautions: Avoid ground water contamination.
Methods for Cleaning Up: Wipe with damp paper towels, Discard properly.

7. Handling and Storage

Store in ventilated, cool, dry place (<25C; 77F); This product is used exclusively for dental purposes by trained personnel

8. Exposure Controls/Personal Protection

Eye Protection: Use protective eyewear.
Hand Protection: Use protective gloves.
Respiratory Protection: Avoid breathing of vapors.
Skin Protection: Use any necessary hygiene measures.

9. Physical / Chemical Properties

Appearance	Gel	Vapor Pressure @ 20C/68F	N/A
Color	Orange	Miscibility	N/A
Odor	Odorless	Vapor Density	N/A
Solubility (H2O, fat)	Miscible	pH	2
Boiling Point / Range	>100 C (212F)	Evaporation Rate	N/A
Melting Point / Range	< 0 C (32F)	Viscosity	N/A
Flash Point	N/A	Partition Coefficient	N/A
Conductivity	N/A	Auto flammability	N/A
Explosive Properties	N/A	Flammability	Non Flammable
Oxidizing Properties	N/A	Relative Density	>1

10. Stability and Reactivity

Avoid high temperatures; Do not store in metal or glass containers.

11. Toxicological Information

Eye Contact:	Causes Burns.
Skin Contact:	Causes burns with delayed tissue destruction, if not removed promptly.
Sensitization:	None known.
Other:	Harmful if inhaled

12. Ecological Information

N/A

13. Disposal Considerations

Refer to any Community provisions relating to waste. In their absence, refer to National or Regional provisions relating to waste.

14. Transport Information

No special precautions.

15. Regulatory Information

Classification:	T Toxic, C Corrosive, R23/24/25 Toxic by inhalation, in contact with skin and if swallowed. R34 Causes burns
Safety:	Refer to any applicable National laws.

16. Other Information

Revision Date: 7/22/2009	Replaces MSDS dated: 2/11/2008
Revision Number: 6	Product: Porc-Etch (Porcelain Etchant)

NOTE: This information is believed to be correct as of the date of this MSDS. The manufacturer makes no representation as to the completeness or accuracy of this information and supplies it on the condition that the person receiving it will make their own determination as to its suitability for their purposes prior to use. In no event will the manufacturer be responsible for damages of any nature whatsoever resulting from the use of or reliance upon the information contained herein.

APPENDIX 4

Material Safety Data Sheet

Issued: 11/14/2008 **Revision Number: 6**

1. Identification of Substance/Preparation and Company/Undertaking

Product Name: Assure Bonding Resin (Assure Primer)
Manufacturer: Reliance Orthodontic Products, Inc., PO Box 678, Itasca, IL 60143
Emergency Telephone: 630-773-4009 Fax: 630-250-7704

Authorized Representative: Emergo Europe, Molenstraat 15, 2513 BH The Hague, The Netherlands
Telephone: +31-70-345-8570 · Fax: +31-70-346-7299

CE Administrator: Amtac Certification Services Ltd., Davey Avenue, Knowlhill, Milton Keynes, MK5 8NL, United Kingdom

2. Composition/Information on Ingredients

Ingredient	Concentration Range (%)	CAS Number	Symbol/Risk Classificaton	OSHA PEL (mg/m3)	ACGIH (mg/m3)	LD50 (mg/kg, rat/oral)
Biphenyl Dimethacrylate	>10	125086-31-9	Xi, R36/38-43	N/D	N/D	N/D
Hydroxyethyl methacrylate	>10	868-77-9	Xi; R43	N/D	N/D	5050
Acetone	>40	67-64-1	F, R11, Xi R36-66-67	2400	1187	5800

N/A = not applicable, N/D = not determined,

3. Hazards Identification

Flammable – Highly flammable. Irritant – Irritating to the eyes and skin. May cause sensitization by skin contact. Repeated exposure may cause skin dryness or cracking. Vapors may cause drowsiness and dizziness.

4. First-aid Measures

Inhalation: Provide fresh air and rest.
Skin Contact: Wash with soap and water.
Eye Contact: In case of contact with eyes, rinse immediately with plenty of water and seek medical attention.
Ingestion: Drink two glasses of water or milk. Seek medical attention if a substantial amount has been ingested.

5. Fire-fighting Measures

Fire-fighting media: Dry chemical powder, foam or carbon dioxide.
Fire and explosion risks: Upon combustion, irritating gases may form.

6. Accidental Release Measures

Personal Precautions: Prevent skin/eye contact, Provide ventilation.
Environmental Precautions: Avoid ground water contamination.
Methods for Cleaning Up: Wipe with damp paper towels, Discard properly.

7. Handling and Storage

Avoid high light intensity >10000 lux, this product is used exclusively for dental purposes by trained personnel. Store in a cool, dry place (less than 25 Degrees C).

8. Exposure Controls/Personal Protection

Eye Protection: Use protective eyewear.
Hand Protection: Use protective gloves.
Respiratory Protection: Avoid prolonged breathing of vapors of uncured material.
Skin Protection: Use any necessary hygiene measures.

9. Physical / Chemical Properties

Appearance	Liquid	Vapor Pressure @ 20C/68F	182 mm/Hg
Color	Straw	Miscibility	N/A
Odor	Slight odor of Acetone	Vapor Density	2
Solubility (H2O, fat)	Miscible	pH	4.3- 4.5
Boiling Point / Range	>56 C / 133F	Evaporation Rate	14.2
Melting Point / Range	<0C / 32 F	Viscosity	N/A
Flash Point	-19 C / -2 F	Partition Coefficient	N/A
Conductivity	N/A	Autoflammability	N/A
Explosive Properties	N/A	Flammability	Flammable
Oxidizing Properties	N/A	Relative Density	N/A

10. Stability and Reactivity

Avoid high temperatures.

11. Toxicological Information

Eye Contact:	Irritates the eyes.
Skin Contact:	Irritates the skin.
Sensitization:	May cause allergic reaction on contact with the skin.
Other:	Repeated exposure may cause skin dryness or cracking. Vapors may cause drowsiness and dizziness.

12. Ecological Information

N/A

13. Disposal Considerations

Refer to any Community provisions relating to waste. In their absence, refer to National or Regional provisions relating to waste.

14. Transport Information

No special precautions.

15. Regulatory Information

Classification:	Xi Irritant, F Flammable, R11 Highly flammable., R36 Irritating to eyes., R38 Irritating to skin., R43 May cause sensitization by skin contact. R66 Repeated exposure may cause skin dryness or cracking. R67 Vapors may cause drowsiness and dizziness.
Safety:	Refer to any applicable National laws.S(2-)9-16-26. Keep out of reach of children. Keep container in a well ventilated place. Keep away from sources of ignition. In case of contact with eyes, rinse immediately with plenty of water and seek medical advice.

16. Other Information

Revision Date: 11/14/2008	Replaces MSDS dated: 2/8/08
Revision Number: 6	Product: Assure Bonding Resin (Assure Primer)

NOTE: This information is believed to be correct as of the date of this MSDS. The manufacturer makes no representation as to the completeness or accuracy of this information and supplies it on the condition that the person receiving it will make their own determination as to its suitability for their purposes prior to use. In no event will the manufacturer be responsible for damages of any nature whatsoever resulting from the use of or reliance upon the information contained herein.

APPENDIX 5

Material Safety Data Sheet

Issued: 8/11/2008 **Revision Number: 6**

1. Identification of Substance/Preparation and Company/Undertaking

Product Name: Porcelain Conditioner (Porcelain Primer)
Manufacturer: Reliance Orthodontic Products, Inc., PO Box 678, Itasca, IL 60143
Emergency Telephone: 630-773-4009 Fax: 630-250-7704

Authorized Representative: Emergo Europe, Molenstraat 15, 2513 BH The Hague, The Netherlands
Telephone: +31-70-345-8570 · Fax: +31-70-346-7299

CE Administrator: Amtac Certification Services Ltd., Davey Avenue, Knowlhill, Milton Keynes, MK5 8NL, United Kingdom

2. Composition/Information on Ingredients

Ingredient	Concentration Range (%)	CAS Number	Symbol/Risk Classification	OSHA PEL (ppm)	ACGIH (ppm)	LD50 (mg/kg, rat/oral)
Ethanol	30-70	64-17-5	F, R11	1000	N/D	N/D
Acetone	30-70	67-64-1	F, R11,Xi	1000 N/D	750/ 1000 STEL	5800
Silane	1-10	2530-85-0	R36/37/38		N/D	N/D

3. Hazards Identification

Flammable. Irritates the eyes and respiratory system. May cause allergic reaction on skin

4. First-aid Measures

Inhalation: Provide fresh air and rest.
Skin Contact: Wash with soap and water.
Eye Contact: Flush with running water for at least 15 minutes while keeping eye lids open; seek medical attention.
Ingestion: Drink two glasses of water or milk. Seek medical attention if a substantial amount has been ingested.

5. Fire-fighting Measures

Fire-fighting media: Dry chemical powder, foam or carbon dioxide.
Fire and explosion risks: Upon combustion, irritating gases may form.

6. Accidental Release Measures

Personal Precautions: Prevent skin/eye contact, Provide ventilation.
Environmental Precautions: Avoid ground water contamination.
Methods for Cleaning Up: Wipe with damp paper towels, Discard properly.

7. Handling and Storage

Avoid high light intensity >10000 lux, this product is used exclusively for dental purposes by trained personnel

8. Exposure Controls/Personal Protection

Eye Protection: Use protective eyewear.
Hand Protection: Use protective gloves.
Respiratory Protection: Avoid prolonged breathing of vapors of uncured material.
Skin Protection: Use any necessary hygiene measures.

9. Physical / Chemical Properties

Appearance	Liquid	Vapor Pressure @ 20C/68F	232 mmHg
Color	Clear	Miscibility	N/A
Odor	Acetone	Vapor Density	N/A
Solubility (H2O, fat)	Soluble	pH	N/A
Boiling Point / Range	N/A	Evaporation Rate	N/A
Melting Point / Range	N/A	Viscosity	N/A
Flash Point	-18 Degrees C / -8 Degrees F	Partition Coefficient	N/A
Conductivity	N/A	Autoflammability	No
Explosive Properties	N/A	Flammability	Yes
Oxidizing Properties	N/A	Relative Density	N/A

10. Stability and Reactivity

Avoid high temperatures.

11. Toxicological Information

Eye Contact:	Irritates the eyes.
Skin Contact:	May irritate the skin.
Sensitization:	May cause allergic reaction on contact with the skin.
Other:	N/A.

12. Ecological Information

N/A

13. Disposal Considerations

Refer to any Community provisions relating to waste. In their absence, refer to National or Regional provisions relating to waste.

14. Transport Information

No special precautions.

15. Regulatory Information

Classification:	F Flammable, R11 Highly Flammable, Xi Irritant, R36 Irritating to eyes. R37 Irritating to respiratory system. R38 Irritating to skin.
Safety:	Refer to any applicable National laws.

16. Other Information

Revision Date: 8/11/2008	Replaces MSDS dated: 2/11/2008
Revision Number: 6	Product: Porcelain Conditioner (Porcelain Primer)

NOTE: This information is believed to be correct as of the date of this MSDS. The manufacturer makes no representation as to the completeness or accuracy of this information and supplies it on the condition that the person receiving it will make their own determination as to its suitability for their purposes prior to use. In no event will the manufacturer be responsible for damages of any nature whatsoever resulting from the use of or reliance upon the information contained herein.

APPENDIX 6

Scientific poster presentations based on this Master's project :

1. American Association of Orthodontists Annual Conference, Honolulu 2012
2. Journées Dentaires du Québec conférence annuelle, Montréal 2012
3. Canadian Association of Orthodontists Annual Session, Ottawa 2012
4. American Association of Orthodontists Annual Conference, Philadelphia 2013; candidate for the Charley Schultz Resident Scholar Award in the Basic Science category. Recipient of the Charley Schultz Travel Bursery.